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Development of Low-Profile Barrier Features for Space-Restrictive Applications

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16. Abstract

In a previous FDOT research project, a low-profile concrete safety barrier was developed for use in roadside work zone environments. The barrier was designed using finite element impact analysis techniques (computer simulations). Subsequently, the barrier was successfully crash tested to validate its performance. In the present study, vehicle and barrier finite element models (developed in the previous study) are calibrated using results from full-scale crash testing. The calibrated models are then used to conduct parametric studies for the purposes of: 1) determining the relationship between vehicle impact speed and lateral barrier deflection, and 2) assessing the performance of the barrier in various drop-off zone configurations. Data obtained from the parametric studies are used to evaluate possible means of minimizing the lateral space that must be allocated for the use of barriers on roadway design projects. New relationships between vehicle impact speed and lateral deflection are developed so that installation options (e.g., reducing the speed limit within a work-zone) are available in space-restricted applications. Similarly, data relating to the minimum deflection space required for adequate barrier performance in drop-off type applications are developed.

In addition, a new crashworthy end-treatment has been developed that will permit barrier installations to be abruptly ended in space-restrictive situations (e.g., areas having a high density of cross-roads, driveways). The new end-treatment is 20 ft. long, is composed of a 12 ft. long concrete segment and an 8 ft. steel segment, and tapers from 18 in. to 2 in. in height. An innovative connection system and a nearly symmetric shape make the end-treatment reversible. This reversibility permits the end-treatment to be attached to either the key or keyway ends of low-profile barrier segments. Finite element impact analyses are used to determine the geometric shape of the system and to establish design forces. Subsequently, the end-treatment is structurally-designed, fabricated, and subjected to a series of seven full-scale crash tests per the test level 2 requirements of NCHRP Report 350. Crash tests involving both a small car (820kg) and a full-size pickup truck (2000 kg) are successfully passed.

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EXECUTIVE SUMMARY

In a previous FDOT research project, a low-profile concrete safety barrier was developed for use in roadside work zone environments. The barrier was designed using finite element impact analysis techniques (computer simulations). Subsequently, the barrier was successfully crash tested to validate its performance. In the present study, vehicle and barrier finite element models (developed in the previous study) are calibrated using results from full-scale crash testing. The calibrated models are then used to conduct parametric studies for the purposes of: 1) determining the relationship between vehicle impact speed and lateral barrier deflection, and 2) assessing the performance of the barrier in various drop-off zone configurations. Data obtained from the parametric studies are used to evaluate possible means of minimizing the lateral space that must be allocated for the use of barriers on roadway design projects. New relationships between vehicle impact speed and lateral deflection are developed so that installation options (e.g., reducing the speed limit within a work-zone) are available in space-restricted applications. Similarly, data relating to the minimum deflection space required for adequate barrier performance in drop-off type applications are developed.

In addition, a new crashworthy end-treatment has been developed that will permit barrier installations to be abruptly ended in space-restrictive situations (e.g., areas having a high density of cross-roads, driveways). The new end-treatment is 20 ft. long, is composed of a 12 ft. long concrete segment and an 8 ft. steel segment, and tapers from 18 in. to 2 in. in height. An innovative connection system and a nearly symmetric shape make the end-treatment reversible. This reversibility permits the end-treatment to be attached to either the key or keyway ends of low profile barrier segments. Finite element impact analyses are used to determine the geometric shape of the system and to establish design forces. Subsequently, the end-treatment is structurally-designed, fabricated, and subjected to a series of seven full-scale crash tests per the test level 2 requirements of NCHRP Report 350. Crash tests involving both a small car (820kg) and a full-size pickup truck (2000 kg) are successfully passed.

Tapered steel and concrete end-treatment segments connected to low-profile barrier

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1. INTRODUCTION

In a previous research study (Consolazio et al. 2003), a new low-profile safety barrier (Figure 1) was developed for use in roadside work zones. Computer simulations and full-scale crash testing were used to design the new system and validate its performance according to nationally accepted standards (NCHRP Report 350 (1993), Test Level 2 requirements). As a result of the unique manner in which the barrier segments are interconnected in this system, both horizontally and vertically curved alignments can be achieved. In addition, the system is only 18 in. in height and is constructed from modular, easily installable and easily replaceable concrete segments.

Rather than relying on mechanical anchoring between the barrier and the roadway surface, the low-profile barrier instead utilizes inertial (mass-related) resistance to redirect vehicles that might otherwise errantly enter a work-zone. Since the barrier system is somewhat flexible and not rigidly attached to the ground surface, the segments deflect when impacted by a vehicle. The degree of lateral barrier deflection is determined by many factors including vehicle impact speed, vehicle impact angle, frictional resistance between the bottom of the barrier and the roadway, inertial resistance of the barrier system, and the stiffness of the segment-to-segment connection elements. Assuming fixed (non-changing) system characteristics such as section geometry, connector stiffness, etc., one of the goals of the study presented in this report is to establish a quantitative relationship between vehicle impact speed and maximum sustained lateral deflection. Such information can provide insight into the utility of reducing speed limits in works zones that have extremely limited space available for lateral barrier deflection.

When crash-tested by a 2000 kg pickup truck at 45 mph (25 degree impact angle), the measured lateral deflection of the low-profile barrier segments was approximately 9 in. An additional goal of the present study is to determine the minimum lateral deflection space (9 in. or less) that must be provided in order to ensure adequate barrier performance. For example, if the back (non-impact) face of the barrier is located less than 9 in. from a vertical drop in the roadway surface, it is of interest to determine whether the barrier will remain stable and capable of vehicle-redirection despite the reduced deflection space.

a) Individual barrier segment

b) Segments attached together to form a curved barrier

Figure 1. Low-Profile Safety Barrier

Finally, the most significant task undertaken in this study involves the development of a crash-worthy end-treatment that will permit barrier installations to be abruptly ended in space-restrictive situations (e.g., areas having a high density of cross-roads, driveways). In current practice, barrier segments must be flared away from the roadway near the end of an installation so that vehicles are protected from the possibility of striking the blunt up-stream or down-stream ends of the concrete segments. In this study, a new tapered end-treatment is developed that can be attached directly to the ends of a barrier installation, thereby eliminating the need to flare the barrier segments away from the roadway. Computer simulations are used to design an end-treatment that is crashworthy when struck by small cars (820 kg) and full-size pickup trucks (2000 kg) at varying locations, offsets, and impact angles. A series of seven full-scale crash tests, conducted in accordance with the test level 2 requirements of NCHRP Report 350, are then carried out to validate the performance of the newly developed end-treatment.

2. POTENTIAL MEANS OF REDUCING LATERAL SPACE REQUIREMENTS

The low-profile roadside safety barrier was designed using computer simulation techniques and subsequently validated using full-scale crash testing in accordance with NCHRP Report 350. Detailed descriptions of the modeling methods used in the previous study are described in Consolazio et al. (2003). In the present study, pickup truck and barrier finite element models (developed during the earlier study) are calibrated using key results from the full-scale crash test program.

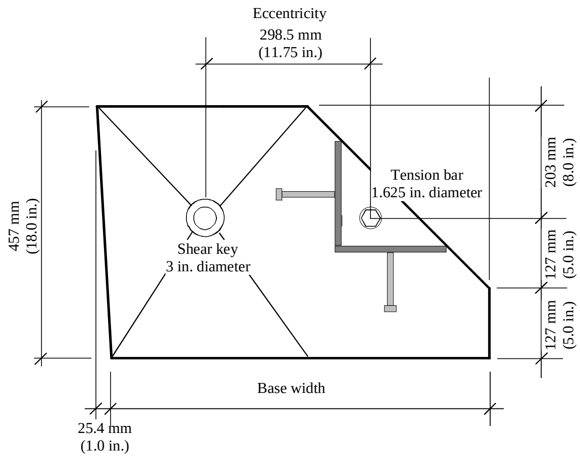
2.1 Overview of finite element model

Sketches of the physical dimensions of the barrier cross-section are given in Figure 2. The behavior of the vertical shear channel is modeled with nodal constraints allowing segments to move individually in the vertical direction, but in a constrained-fashion laterally (i.e. only lateral compatibility between segments is maintained). Contact definitions are used to model the fact that the shear pin also transmits compression via direct contact with the adjacent segment, but does not transmit tension. In this manner, an opening-and-closing gap mechanism at the joints is simulated (Figure 3). Each tension rod is modeled using a discrete nonlinear spring element for which the tensile material parameters are selected to match the diameter and material stiffness of high strength steel (150 ksi) threaded rod. As a consequence of the manner in which the bolts are connected to the barrier segments, the compressive behavior of each tension rod is modeled with zero-stiffness (see Consolazio et al. 2003 for detailed discussions of bolt modeling).

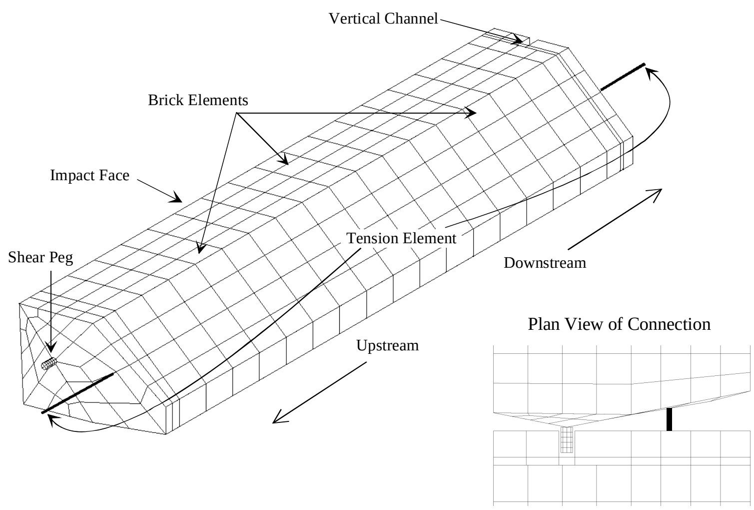
2.2 Calibration of the finite element model using crash test results

In the full-scale pickup truck (2000P) crash test that was conducted to validate performance of the barrier per NCHRP Report 350, the vehicle impacted the barrier at a 25 degree angle and exited at a zero-degree angle with minimal damage to the truck. Maximum lateral deflection of the barrier into the hypothetical work zone located behind the system was limited to approximately 9 in. even though the barrier was not anchored to the roadway. Occupant-risk measures were within allowable limits. Even with its low vertical profile (18 in. height), the barrier was able to redirect the 2000 kg vehicle without the occurrence of rollover, barrier connection failure, or vehicle snagging.

Using data from the crash test, the previously developed finite element model is improved through calibration (also referred to as “tuning”). The first step in this process involves modeling the actual field conditions of the crash tests as accurately as possible. Given the inherent difficulties involved in controlling a full-scale vehicle crash test, NCHRP 350 permits tests conditions to deviate from the target conditions as long as the actual tested conditions are within a specified window of acceptability. In the case of the 2000P low-profile barrier crash test, the actual impact speed was 67.4 km/h (41.9 mph) which was acceptably close (per NCHRP Report 350) to the target speed of 72 km/h (45 mph).

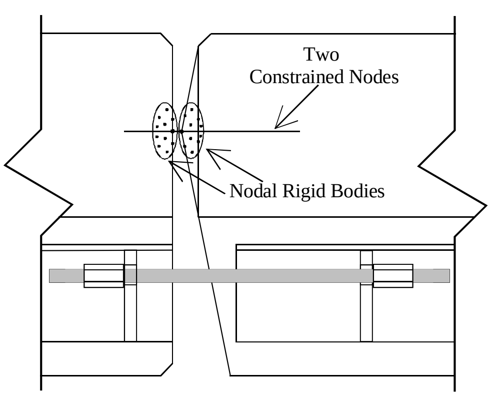


a) Cross-section

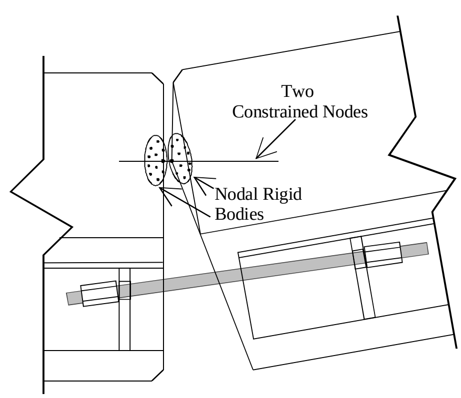


b) Finite element model of a single barrier segment

Figure 2. Schematic diagram of low-profile safety barrier



a) Before impact



b) During/after impact

Figure 3. Finite element modeling of shear connection

Accordingly, the computer simulations are performed for the low-profile safety barrier finite element model using the actual vehicle impact speed of 67.4 km/h (41.9 mph) rather than the target speed of 72 km/h (45 mph). Results obtained from the full-scale 2000P test and from the corresponding numerical simulation are shown in Table 1. Results from the 2000P test are generally in good agreement with the simulation data. Overall vehicle motions and exit angles are in reasonable agreement.

Table 1. Comparison of results after impact speed correction

Impact parameter	Finite element simulation	Full-scale crash test
Impact velocity (mph)	41.9	41.9
Exit velocity (mph)	36.0	30.2
Impact angle (degrees)	25	25
Exit angle (degrees)	0	0
Friction coefficient (barrier-to-roadway)	0.2	0.4~0.5
Max. lateral deflection (in.)	15.0	9.1

The most notable difference is observed between the maximum lateral barrier deflection predicted by finite element simulation and that measured in the physical crash test. As Table 1 indicates, the finite element simulation significantly over-predicts the lateral deflection produced by the impact. This is due primarily to the very low friction coefficient (0.2) used in the numerical simulation. In the earlier barrier design study, simulation was employed as the primary means of arriving at design parameters (connection-bolt force, deflection, vehicle roll angle, etc.). For this reason, a conservatively low friction coefficient was assumed at the time for the purpose of estimating lateral barrier deflection. Since the barrier is not mechanically anchored to the roadway, lateral deflection into the hypothetical work zone is resisted by inertial (mass-related) resistance of the barrier segments and, to a lesser extent, by frictional resistance between the segments and the roadway surface. Thus, use of a low friction coefficient will predictably yield a conservatively large estimation of lateral barrier deflection.

Based on observations made on-site at the crash test facility (E-Tech Testing Services, Rocklin, California), review of photographs and video taken during the crash tests, and additional review of relevant literature, the frictional resistance of the chip-sealed asphalt used in the 2000P test is estimated to be in the range 0.3 to 0.45. Further calibration of the simulation model thus involves the use of friction coefficients in this revised range of values.

Additional comparisons between simulation and crash test results also reveals that the simulation predicts substantial vertical uplifting of the barrier segments on the impact face near the location of contact with the vehicle front tire (Figure 4). High speed video taken during the physical crash test does not, however, show this type of uplifting. During the model calibration process, it was determined that this difference in barrier behavior added to discrepancies in numerically-predicted versus measured lateral barrier deflection.

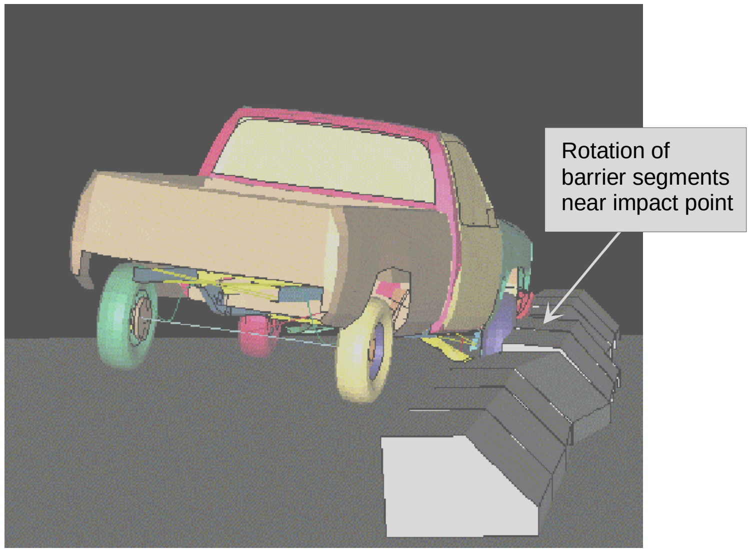


Figure 4. Uplifting barrier segments in computer simulation

One source of difference between the simulation and full-scale testing results was determined to be related to modeling of the vehicle tires. In the 2000P vehicle finite element model used to develop the barrier, the thickness of the shell elements modeling the vehicle tires was chosen to be typical of automotive tires. However, the stiffness of the tire shell elements was substantially increased to prevent inappropriate snagging of the tires on the barrier impact face [a phenomenon that had been observed during development of the first phase barrier system (Ellis et al. 2001)]. In the present study, the thickness of the tire shell elements is preserved but the stiffness is reduced to a more realistic level to more accurately model frictional sliding that occurs between the tires and the barrier. However, even with the improved representation of tire stiffness, the numerically predicted exit velocity of the vehicle (61.5 km/h) is much higher than the exit velocity measured in the crash testing (48.6 km/h). Overall energy dissipation through frictional contact between components of the vehicle (tires, bumper, body panels) and the barrier is thus not being adequately simulated. To overcome this difference, it was also necessary to refine the frictional resistance of metal vehicle parts that contact the concrete barrier during impact so that proper representation of kinetic energy dissipation could be achieved. Dissipated kinetic energy is defined as:

$$E_d = KE_i - KE_f = (1/2)\, m(v_i^2 - v_f^2) \tag{1}$$

where E_d is the total energy dissipated during the impact/contact event; KE_i is the initial kinetic energy; KE_f is the final kinetic energy; *m* is the vehicle mass; and v_i and v_f represent the initial impact velocity and final exit velocity of the vehicle, respectively. Figure 5 illustrates that the modified (tuned) model, incorporating changes both in the tire-to-barrier and metal-to-barrier contacts, produces an improved simulation of the reduction in vehicle velocity (and associated kinetic energy). The numerically predicted resultant velocity of the vehicle model decreases to approximately the exit velocity observed in the full-scale crash test (48.6 km/h, 30.2 mph).

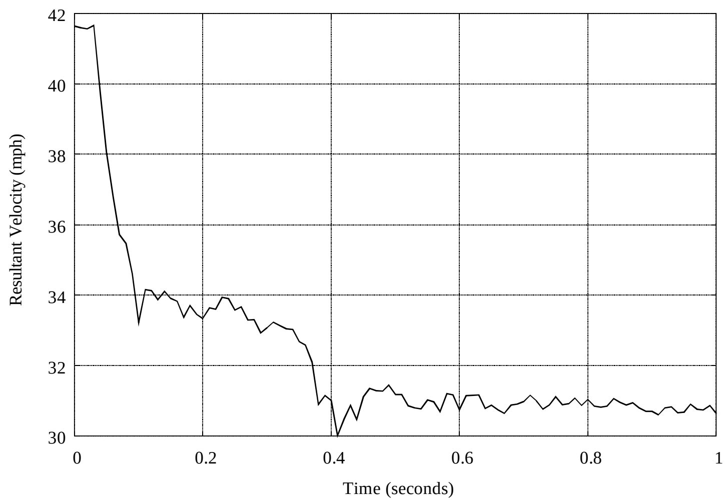


Figure 5. Numerically predicted resultant velocity of modified vehicle model

Further examination of photos of the crash-tested barrier system reveals scrub marks left by the front tire on the impact face of the barrier (Figure 6) and scrape marks that the barrier left on the roadway surface (Figure 7). The latter set of markings reveal that the impacted barriers remained in contact with the roadway while laterally displacing, thus causing abrasion of the roadway surface beneath the barrier. Thus, rigid body motions that uplift the barrier segments (as shown in Figure 4) did not occur in the physical crash tests. Ultimately, this discrepancy between simulation and crash-test is due to the simplified nature of the tire model used in the 2000P vehicle model. Addressing this problem via development of a dramatically improved tire model is beyond the scope of the present study, and, in fact, beyond the scope of most roadside safety studies. Instead, the model was modified to properly simulate the contact between the barriers and the roadway by: 1) restraining vertical motion of nodes along the bottom of the impact face of the barrier segments, and 2) using a friction coefficient of 0.45 that represents frictional resistance of concrete sliding on a chip-sealed asphalt pavement. Incorporating these model modifications, the peak lateral deflection at the impact point on the barrier predicted by simulation (9.2 in. of permanent deflection, see Figure 8) is in good agreement with the crash test result (9.1 in. of permanent deflection, see Table 1).

Figure 6. Indication of tire-scrubbing on impact face of barrier segment

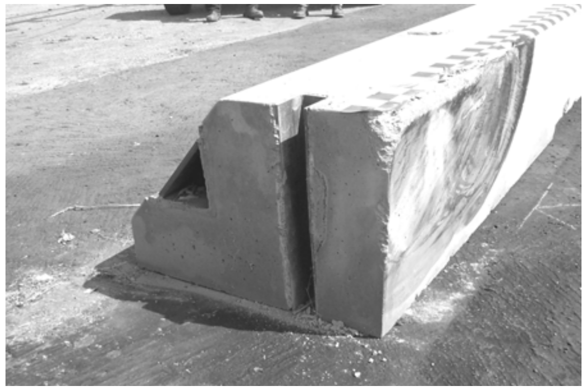


Figure 7. Indication of abrasion between bottom of barrier segment and roadway surface

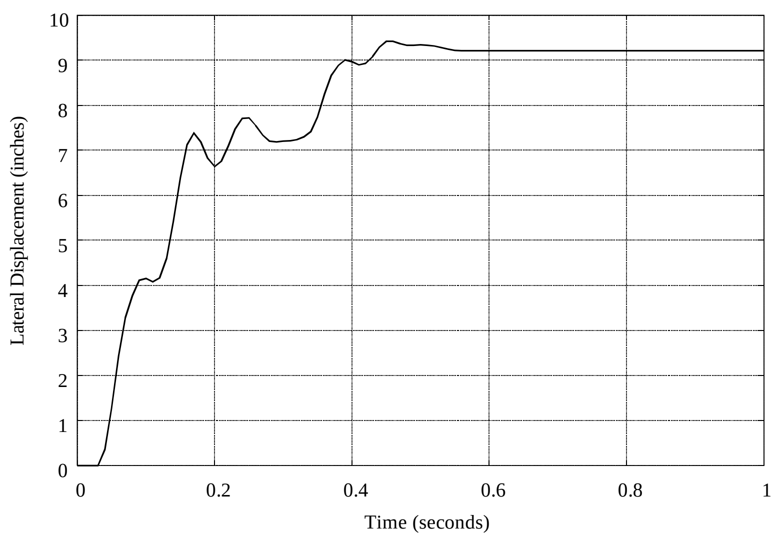


Figure 8. Lateral displacement of barrier at impact point as predicted using the calibrated model

2.3 Relationship between truck impact speed and lateral deflection

Using the tuned finite element model, vehicle impact simulations are now conducted to predict maximum lateral barrier deflections at varying pickup truck impact speeds. Considering limited space availability in work zones, the relationship between truck impact speeds and maximum sustained lateral deflections is of interest in that this information can be used to determine if reduced speed limits can substantially lessen the space requirements associated with installation and deflection the barrier. A set of impact speeds ranging from 30 mph to 45 mph are selected and used to generate four different finite element models (B, C, D, and E of Table 2). These representative barrier models are then bracketed by a lower bound friction of 0.3 and an upper bound friction of 0.45 at varying pickup truck impact speeds. The intent is to bracket the energy dissipation associated with friction forces that were found to be important in the numerical prediction of maximum lateral barrier deflections. In each of these cases, listed as B1 through E2 in Table 2, the mass density of barrier segments was calculated based on the actual weight of the barriers (as indicated in fabrication drawings found in Consolazio et al. 2003). The resulting mass density is 2340 kg/m^3 (146 lbs/ft^3).

Each simulation predicted peak lateral barrier deflections that varied with respect to impact speed. Furthermore, as Figure 9 indicates, lateral displacements of the barrier segments are significantly affected by frictional resistance of the roadway surface. Such variations of displacements tend to increase as the impact speeds increase. For example, as impact speed increases from 30 mph to 45 mph, the differences in prediction of peak deflection at the two friction levels increases from 2.6 in. to 4.2 in., respectively. It is noted that the effects of loss of frictional resistance on the roadway surface due to the presence of surface water will produce a peak lateral barrier displacement of more than 15 in.

Table 2. Finite element models and simulation results

Impact cases	Impact velocity (mph)	Friction coefficient (barrier-to-roadway)	Peak lateral deflection (in.)	Effective width (barrier width plus peak lateral deflection, in.)
A*	41.9	0.45	9.1	37.1
B1	45	0.30	15.4	43.4
B2	45	0.45	11.2	39.3
C1	40	0.30	11.8	39.8
C2	40	0.45	8.9	36.9
D1	35	0.30	9.7	37.7
D2	35	0.45	7.0	35.0
E1	30	0.30	8.1	36.1
E2	30	0.45	5.5	33.5

* FEA model calibrated using low-profile barrier crash-test results

Based on the simulation results, it appears that the effective-width of the barrier (the sum of the physical barrier width plus the maximum lateral barrier deflection during impact) can potentially be reduced to 33.5 in. (Table 2) if the speed limit is limited to 30 mph. However, since this result corresponds to a higher coefficient of friction than might be present at some installation sites, an effective width of 36.1 in.—corresponding to 30 mph but with a lower friction coefficient—is a conservative estimate.

2.4 Effects of drop-off zones on barrier performance

Investigation of the effects of drop-off zones on barrier system performance is also addressed through numerical simulation. The goal is to determine the minimum lateral deflection space (Figure 10) that must be provided for adequate barrier performance and work zone protection in drop-off situations. In these simulations, the vertical nodal constraints introduced in the previously described tuned model have been removed so that conservative estimates of both lateral barrier deflection as well as barrier stability (against rollover) are obtained.

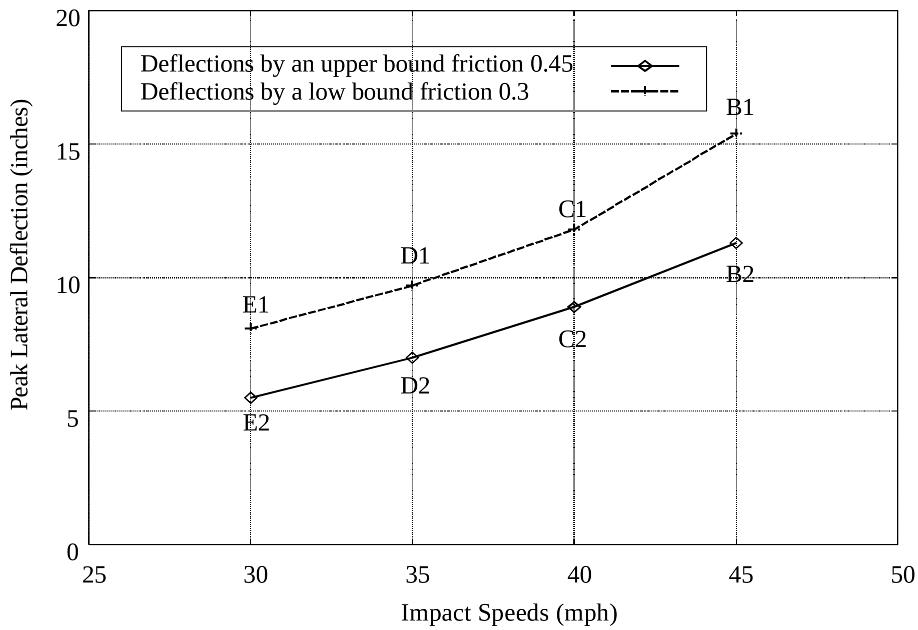


Figure 9. Peak deflections at various impact speeds

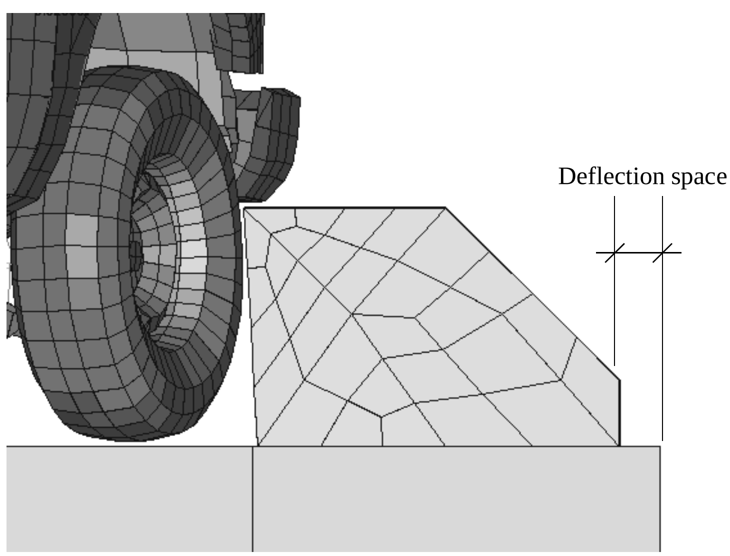


Figure 10. Schematic diagram of typical drop-off zone situation

Three deflection-space widths varying from 0 in. to 6 in. are considered for impact cases B1 and B2 listed in Table 2. In all cases, the vehicle is successfully redirected; however, system failures involving the barrier segments rolling into the work-zone are predicted in cases B1 and B2 when no deflection space is provided (Table 3). Additionally, in cases where only 3 in. of deflection space is provided, barrier stability against rollover is marginal. In this context, marginal performance indicates that while the barrier did not roll into the work zone, introduction of imperfect conditions—such as a deteriorated and ragged roadway edge at the drop-off zone—would lead likely to system failure (barrier rollover). Based on these results, the minimum required lateral deflection space that provides adequate barrier performance is 6 in. for an impact speed of 45 mph.

Table 3. Results of deflection space parameter study

Impact case	Impact velocity (mph)	Friction coefficient (barrier-to-roadway)	Deflection space (in.)	Peak barrier deflection (in.)	Barrier performance
B1	45	0.3	0	19.0	Inadequate
			3	15.1	Marginal
			6	11.9	Adequate
B2	45	0.45	0	16.5	Inadequate
			3	13.1	Marginal
			6	8.9	Adequate

3. END-TREATMENT BACKGROUND INFORMATION

If a vehicle impacts the untreated blunt end of a safety barrier or other fixed object, there is a high probability of occupant injury or fatality since the vehicle is usually brought to a very abrupt stop (i.e, occupants are subjected to large decelerations). Impact with the unprotected end of a longitudinal barrier can also result in barrier or vehicle components penetrating the vehicle passenger compartment, thereby significantly increasing risk to the occupants. Hence, installing a crashworthy end-treatment is considered essential if a barrier is located within the clear zone, and therefore has the potential to be struck head-on by an errant vehicle. Development of a crash-worthy end-treatment for the Florida low-profile barrier began with a review of existing barrier-end-treatment systems. In the following sections, these systems are briefly reviewed in relation to energy absorption/dissipation methods; redirective characteristics; space needed for installation; compatibility with the low-profile work-zone barrier; cost; and, maintenance.

3.1 Gating redirective devices

The Texas Transportation Institute (TTI) (Guidry and Beason 1992) developed and tested a low-profile concrete barrier with a height of 20 in. (compared to the 18 in. height of the Florida low-profile barrier). To provide a matching crash-worthy end-treatment for this system, TTI (Beason 1992, Beason et al. 1998) developed and tested a gating redirective terminal end-treatment that consisted of a concrete tapered section, as shown in Figure 11. The end-treatment is 20 ft. in length, tapers from a maximum height of 20 in. to 4 in. at its tip, and utilizes seven steel anchorage pins (1.25 in. diameter), drilled or driven into the pavement surface, to control lateral deflections during impact.

NCHRP Report 350 defines a gating device, of which the TTI end-treatment is an example, as a system that is “designed to allow controlled penetration of a vehicle when impacted upstream of the beginning of the length of need (LON).” That is, a gating device will permit a vehicle to safely traverse across the device as long as the point of impact is at a location upstream of the portion of barrier that is intended to be redirective.

Figure 11. Safety end barrier for concrete road barriers (Texas Transportation Institute)

3.2 Non-gating redirective devices

In contrast to a gating system, a non-gating redirective terminal will smoothly redirect a vehicle without pocketing or penetration of the system when a vehicle impacts at or near the nose of the device, or downstream of the nose of the device. Examples of such systems include non-gating redirective crash cushions (impact attenuators). Compression attenuators require connections to either a reaction mass or a fixed surface (roadway or wall) to resist impact loads. These devices absorb the kinetic energy of an impacting vehicle using crushable or plastically-deformable cartridges (elements) inside the system. Following a severe impact, the crushed elements are replaced to restore the pre-impact energy absorbing characteristics of the system. Compression attenuators may be used to shield hazards that include the abrupt end of a roadside safety barrier. Examples of compression attenuators that can be used in high-speed (test level TL-3) environments are the QuadGuard CZ System (Figure 12) and the REACT 350 crash cushion (Figure 13) developed by Energy Absorption Systems, Inc.

Figure 12. QuadGuard CZ (Construction Zone) System (Energy Absorption Systems, Inc.)

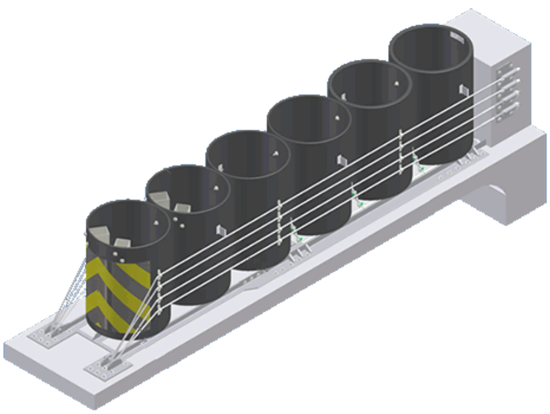


Figure 13. REACT 350 crash cushion (Energy Absorption Systems, Inc.)

3.3 Gating non-redirective devices

A gating non-redirective device absorbs the kinetic energy of an impacting vehicle when struck head-on. When struck at an angle along the side of the device, pocketing and/or penetration of the vehicle into the terminal may result (rather than the vehicle being redirected away from the device), however vehicle-occupant risk measures (e.g., deceleration levels) must still be within acceptable limits. An example of a gating non-redirective device that is currently available is the Triton CET System (Figure 14) developed by Energy Absorption Systems, Inc.

Figure 14. Triton CET System (Energy Absorption Systems, Inc.)

Inertial impact attenuators, which are a form of gating non-redirective crash cushion, reduce the velocity of an errant vehicle by transferring the kinetic energy of the vehicle into an array of relatively massive sub-units that generally undergo permanent inelastic deformation. If sufficient sub-units are provided, anchorage of the system to the roadway and/or barrier may be unnecessary. A common form of inertial attenuator is an array of plastic containers filled with either sand (Figure 15) or water. This type of end treatment is relatively economical, with respect to both manufacturing cost and maintenance.

Figure 15. Typical array of sand barrels

4. END-TREATMENT DEVELOPMENT

4.1 Design goals

All of the end-treatment systems noted above (and additional systems which were also reviewed during this study but which are not explicitly discussed here) are taller than 18 in. in height; the height of the Florida low-profile work-zone concrete barrier. Furthermore, none of these devices have been designed to make use of the unique barrier-to-barrier connection system that is employed in the Florida low-profile barrier system. The unique nature of this connection system is what enables multiple low-profile barrier segments to resist an impacting vehicle using only mass (inertia) and friction, without also requiring positive mechanical anchorage to the roadway surface (e.g. the use of vertical steel pins). To preserve the positive benefits of the low-profile barrier system (e.g., the 18 in. height to provide unobstructed driver views of cross-traffic; no requirement for anchorage to the roadway surface), the following design goals were established in developing a new end-treatment for the Florida low-profile barrier.

- End-treatment shall have a maximum height equal to or less than the height of the low-profile barrier segments (18 in.)
- End-treatment shall not require mechanical anchorage to roadway surface, but instead shall rely on a combination of mass-related inertial resistance and flexural continuity with the low-profile barrier
- End-treatment shall be capable of being connected to the key and/or keyway ends of the low-profile barrier segments using a compatible connection system
- For ease of transportation, handling, and installation, the end-treatment shall be composed of segments that are relatively short in length (no longer than the 12 ft. length of the low-profile barrier segments)
- End-treatment components shall be fabricated from materials that are durable with respect to impact loading, transportation, handling, and installation

Development of an end-treatment design that satisfied these requirements was carried out through a combination of numerical finite element impact simulation and full-scale crash testing per the requirements of NCHRP Report 350.

4.2 Crash test requirements

Full-scale crash tests conducted on the Florida low-profile barrier (Consolazio et al. 2003) were carried out in accordance with the longitudinal barrier requirements of NCHRP Report 350. Testing was conducted at test level 2 (TL-2) conditions (45 mph impact speed), hence the design and testing of the end-treatment shall also correspond to 45 mph impact conditions. The newly developed end-treatment shall be designed and tested as a gating terminal device. Based on NCHRP Report 350, the following crash tests are required for a gating end-terminal (descriptions have been adapted from Beason et al. 1998):

- <u>NCHRP 350 test designation 2-30</u>. This test involves an 820 kg passenger vehicle approaching parallel to the road way and impacting the end-treatment at a nominal speed and angle of 43.5 mph (70 km/h) and 0-degrees with the quarter point of vehicle aligned with the centerline of the end-treatment. This test is intended to evaluate occupant risk and vehicle trajectory.

- NCHRP 350 test designation 2-31. This test involves a 2000-kg pickup truck impacting the end-treatment at a nominal speed and angle of 43.5 mph (70 km/h) and 0-degrees with the center line of vehicle aligned with the centerline of the end-treatment. The purpose of this test is to evaluate the capacity of the end-treatment to absorb the kinetic energy of the 2000-kg vehicle (in terms of structural adequacy criteria) in a safe manner (occupant risk).
- NCHRP 350 test designation 2-32. This test involves an 820-kg passenger vehicle impacting the end-treatment at a nominal speed and angle of 43.5 mph (70 km/h) and 15-degrees with the center line of the vehicle aligned with the centerline of the nose of the end-treatment. This test is intended to evaluate occupant risk and vehicle trajectory.
- NCHRP 350 test designation 2-33. This test involves a 2000-kg pickup truck impacting the end-treatment at a nominal speed and angle of 43.5 mph (70 km/h) and 15-degrees with the center line of the vehicle aligned with the centerline of the nose of the end-treatment. This test is intended to evaluate occupant risk and vehicle trajectory.
- NCHRP 350 test designation 2-34. This test involves an 820-kg passenger vehicle impacting the end-treatment at a nominal speed and angle of 43.5 mph (70 km/h) and 15-degrees with the front corner of the vehicle aligned with the critical impact point (CIP) of the end-treatment (location of the critical point is subject to judgment based on test experience with similar devices or computer simulation).
- NCHRP 350 test designation 2-35. This test involves a 2000-kg pickup truck impacting the end-treatment at a nominal speed and angle of 43.5 mph (70 km/h) and 20-degrees with the front corner of the vehicle impacting at the beginning of the length of need (LON). This test is intended to evaluate the ability of the end-treatment to contain and redirect the pickup truck within vehicle trajectory criteria.
- NCHRP 350 test designation 2-39. This test involves a 2000-kg pickup truck impacting the end-treatment from the reverse direction at a nominal speed and angle of 43.5 mph (70 km/h) and 20-degrees at the mid-length of the end-treatment. This test is intended to evaluate the performance of the end-treatment for a reverse impact.

Recall that a fundamental design goal in developing the Florida low-profile barrier was to minimize barrier height while still providing adequate resistance against vehicle rollover during NCHRP Report 350 testing. During that development process, it was determined that a barrier with a height of less than 18 in. would not likely provide the necessary level of safety with regard to vehicle redirection and resistance to vehicle rollover. Consequently, in the development of an end-treatment that will begin at a height of 18 in. (at the point of connection to the low-profile barrier) and which will taper downward in height from that point, there is no expectation that the end-treatment itself will be capable of redirecting a full-size pickup truck in a stable manner. For this reason, no part of the end-treatment is considered to contribute to the length of need (LON) of barrier that is required to protect a particular work-zone.

4.3 Conceptual development using finite element analysis (FEA)

Conceptual development of the new end-treatment was carried out using computer simulation techniques, specifically finite element impact analysis. As in previous related studies (Ellis et al. 2001, Consolazio et al. 2003), the LS-DYNA explicit dynamic finite element analysis code (LS-DYNA 2003) was employed in the current study. Conceptual development focused primarily on determining a geometric shape, mass, and stiffness of the end-treatment such that the system would perform adequately in all seven of the required NCHRP Report 350 crash test conditions. Once an acceptable end-treatment concept was developed, dynamic internal forces were computed from the simulation results and separate structural design calculations were used to choose reinforcing steel, material (concrete, steel) strengths, plate thicknesses, bolt sizes, and weld sizes.

For each geometric configuration of end-treatment that was considered, a minimum of seven separate impact analyses were performed. In each analysis, one of the NCHRP Report 350 test vehicles (an 820 kg car or a 2000 kg truck) was simulated striking an overall system consisting of the end-treatment connected to a series of ten low-profile barrier segments. The 820 kg small car (denoted the 820C vehicle by NCHRP Report 350) and 2000 kg pickup truck (denoted 2000P by NCHRP Report 350) vehicle models used in this study were obtained from the National Crash Analysis Center (NCAC) and subsequently modified. During the previous study, in which the low-profile barrier segment was developed (Consolazio et al. 2003), only impacts involving the 2000P vehicle were simulated since this vehicle was deemed more critical from the perspectives of both maximum design forces and maximum likelihood for vehicle rollover. Furthermore, the NCHRP Report 350 test conditions for concrete longitudinal barriers do not produce situations in which the underside of the vehicle interacts, to any significant extent, with the barrier. Hence, it was not necessary to use a model with a detailed representation of the underside of the vehicle. Consequently, in that study, the only vehicle model employed was the *reduced-resolution* version of the NCAC Chevy C2500 pickup truck (2000P) model.

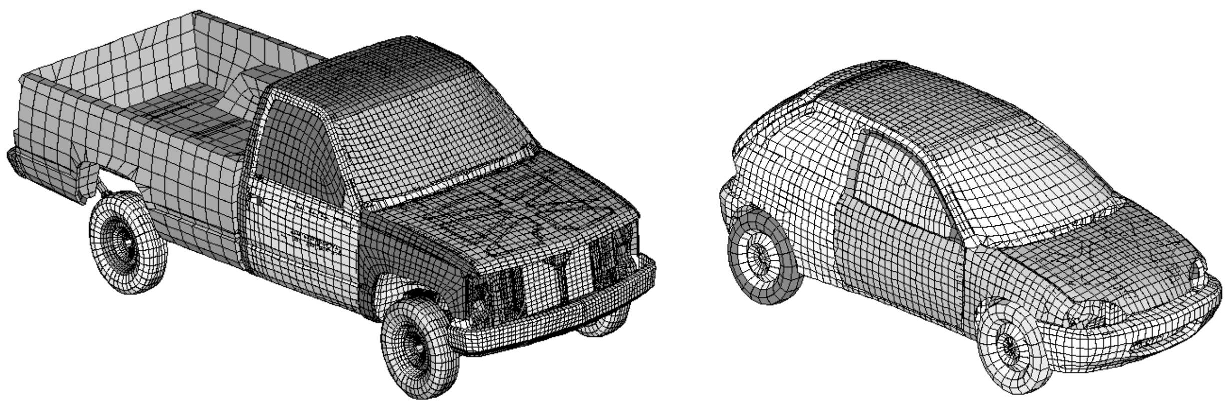
In contrast, the same approach was not viable in developing an end-treatment for the low-profile barrier. Although tests involving the 2000P vehicle were once again expected to generate the largest structural design forces, in several of the tests, the 820C small car was expected to be the more critical vehicle in terms of maintaining vehicle stability and avoiding rollover. Furthermore, several of the test conditions involved the vehicles riding up on the end-treatment, thereby producing significant interaction between the undersides of the vehicle models and the end-treatment and connected barrier segments. The level of detail modeled in the underside of the reduced-resolution Chevy C2500 model used previously was insufficient for use in end-treatment simulations. As a result, new finite element vehicle models (Figure 16) were obtained from the NCAC for this study: a *high-resolution* model of a Chevy C2500 pickup (2000P) and a *high-resolution* model of a Geo Metro small car (820C). In Figure 17, the reduced-resolution pickup truck model used in the previous study is compared to the high-resolution model used in the present study. Clearly evident in the figure is the fact that the reduced-resolution model lacks detailed modeling of several vehicle components (e.g., rear axle and differential case) that have the potential to come into contact with, and interact with, the top surfaces of the end-treatment and the connected barrier segments.

As was the case in previous studies (e.g., Consolazio et al. 2003), the vehicle models obtained from NCAC for this study were modified prior to use in the end-treatment impact simulations. Modifications included:

- Contact surfaces were defined for the underside of the vehicle models to permit the vehicles to contact and interact with surfaces of the end-treatment and barrier segments
- Finite element formulations for several vehicle components were changed from numerically-efficient under-integrated formulations to more numerically-intensive, but more accurate and more stable, fully-integrated element formulations.

- Material models for some vehicle components were updated to improve the stability of the overall numerical simulation process
- Thicknesses of shell elements modeling tire walls were given realistic values
- Minor modifications were made to initial nodal velocities to improve the consistency between the translation of the vehicles and the angular velocities of the tire/wheel assemblies
- Suspension stiffnesses and pre-compression levels under gravity loading were updated
- Nodal coordinates of selected shell element nodes were shifted to eliminate initial-penetration contact problems and thereby improve the numerical stability of the simulation process

In each vehicle impact simulation conducted, the end-treatment was connected to a series of ten low-profile barrier segments. Physically, the barrier segments are connected together using high-strength steel (150 ksi) threaded bar. The method used to model the threaded bar involved the use of discrete spring elements, inelastic tensile behavior, and zero compressive stiffness.

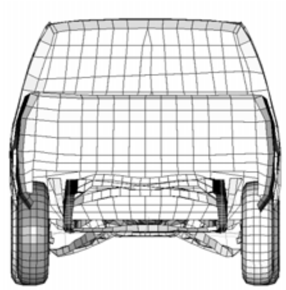


a) 2000 kg pickup truck b) 820 kg small car

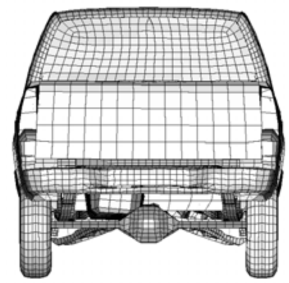
Figure 16. Finite element models of test vehicles

This modeling process used here is the same as that used in the previous barrier development study and is documented in detail in Consolazio et al. (2003).

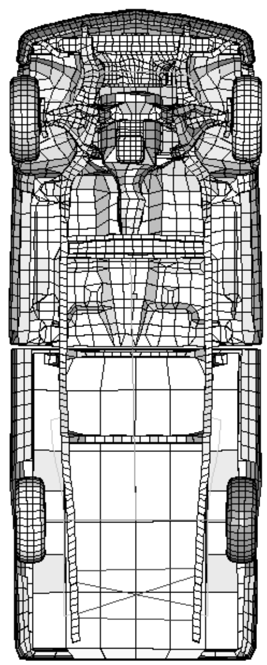
In total, more than half a dozen different geometric concepts were considered for the end-treatment. For each concept, the full matrix of NCHRP Report 350 tests was numerically simulated to evaluate vehicle stability during and after impact. Ultimately, the most promising design concept consisted of an end-treatment 20 ft. in length, which tapers both vertically (in height) and horizontally (in width). In the vertical direction, the height varies from a maximum of 18 in. (at the point of connection to the low-profile barrier) to a minimum of 2 in., with the vertical taper occurring over two sections that have moderately different slopes. Horizontally, the width of the end-treatment tapers from a maximum of 28 in. to a minimum of 16 in. The side surfaces of the end-treatment are vertical, rather than negatively sloped as is the case in the low-profile barrier segments.



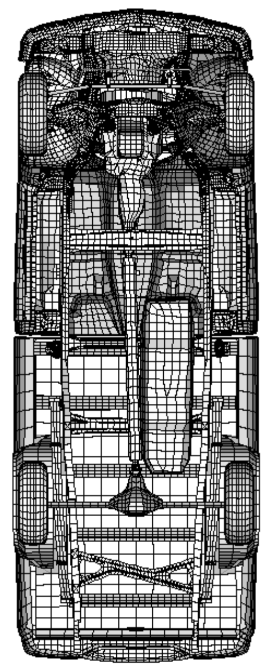
a) Rear of reduced -resolution
2000 kg pickup model



c) Rear of high-resolution
2000 kg pickup model



b) Underside of reduced-resolution
2000 kg pickup model



d) Underside of high-resolution
2000 kg pickup model

Figure 17. Finite element models of test vehicles

Numerical models corresponding to NCHRP 350 test conditions 2-30 and 2-31 are shown in Figures 18 and 19, respectively. Each of these tests corresponds to a head-on impact condition (0-degree impact angle). Test 2-30 is conducted with the centerline of the 820C vehicle offset from the centerline of the tip (nose) of the end-treatment, whereas in test 2-31, the centerline of the 2000P vehicle is aligned with the centerline of the end-treatment.

It should be noted that the geometric form of end-treatment models presented in this section differ in some very minor ways from the final design that was crash tested. For example,

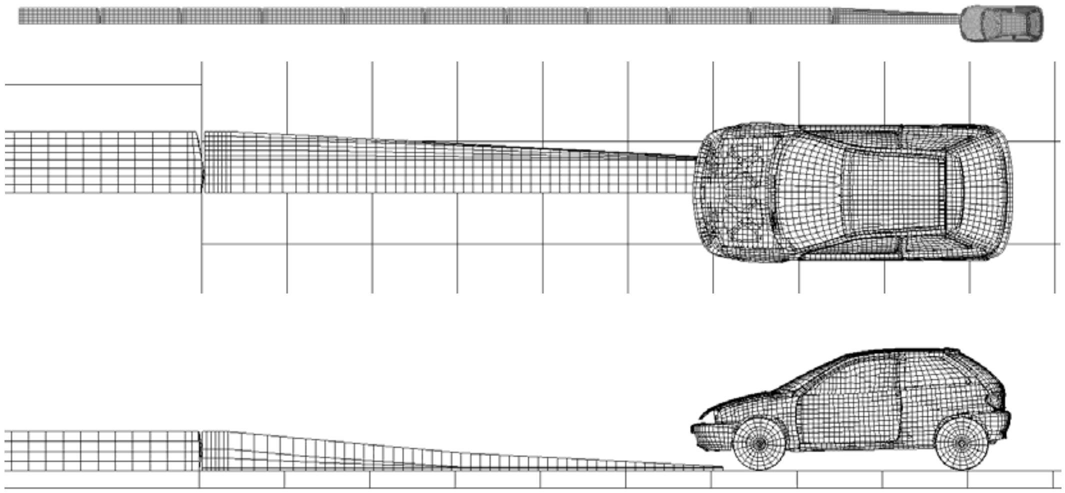


Figure 18. Finite element model of test 2-30 (820 kg car)

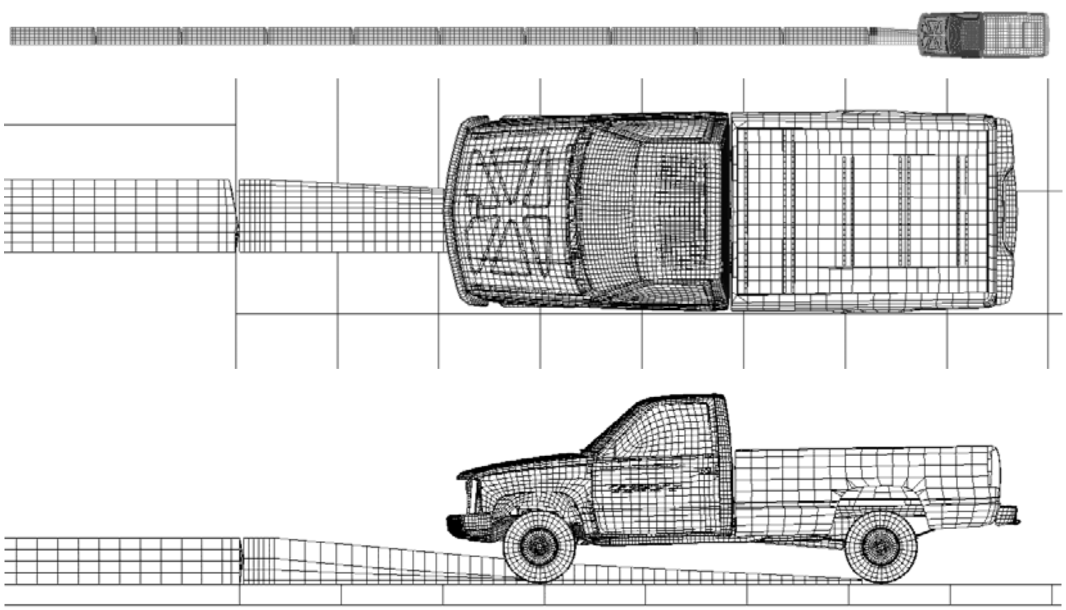


Figure 19. Finite element model of test 2-31 (2000 kg truck)

the short constant-height section at the tall-end of the end-treatment was later replaced during the structural design process with a taper that extends all the way to the end of the end-treatment. Also, for simulation purposes, the entire 20 ft. end-treatment was analyzed as a single, contiguous unit. During the structural design stage, the 20 ft. segment was subdivided into two separate, field-connectable components. The total distribution of mass within the finite element model and in the final structural design was, however, kept consistent.

In Figure 20 and 21, models corresponding to NCHRP 350 test conditions 2-32 and 2-33 are shown. Each of these cases consists of a vehicle striking the end-treatment at an oblique angle of 15-degrees, with the centerline of the vehicle aligned with the centerline of the tip of the end-treatment.

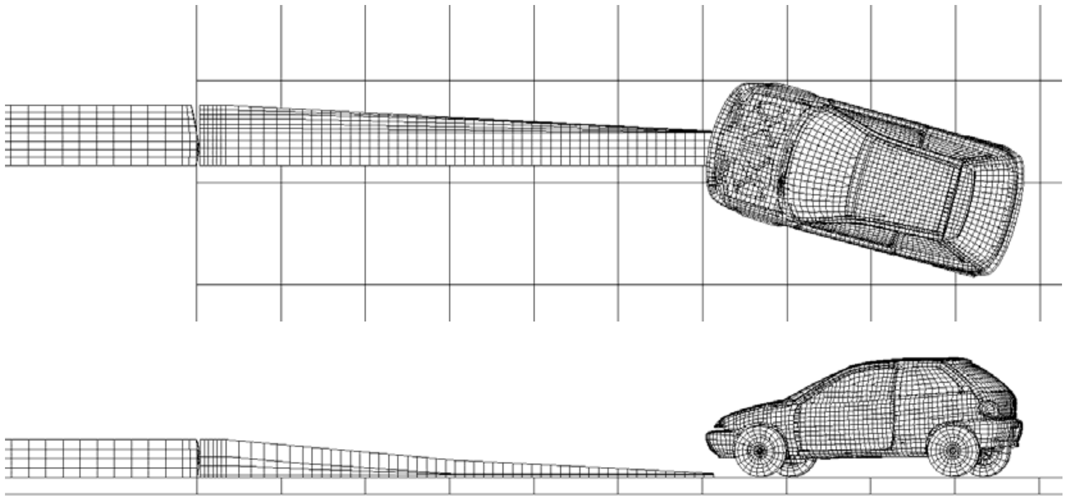


Figure 20. Finite element model of test 2-32 (820 kg car, 15-deg. angle)

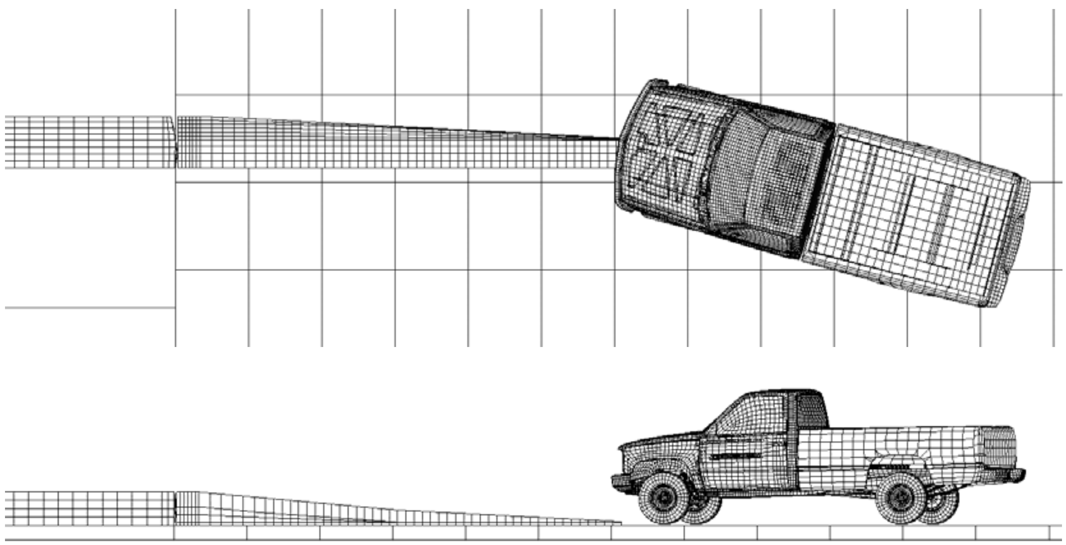


Figure 21. Finite element model of test 2-33 (2000 kg truck, 15-deg. angle)

In Figure 22, the model corresponding to NCHRP 350 test condition 2-34 is shown. Test 2-34 involves a 15-degree oblique impact of a 820C vehicle striking the end-treatment at the critical impact point (CIP). With regard to selecting the CIP for test 2-34, NCHRP Report 350 states:

> Therefore, selection of the CIP for Test 34 should be based on test experience with similar devices, computer simulation if possible, and judgment. In selecting the CIP, consideration should not only be given to the point with the greatest potential for causing

> snagging or pocketing but also the point with the greatest potential for producing vehicular overturn. For example, in testing a sloped end terminal, vehicular stability is the primary concern, not snagging or pocketing, and the CIP may not be midway between the end of the terminal and the beginning of the LON. In the absence of a determinable CIP, Test 34 may be conducted with the initial impact point midway between the end of the device and the beginning of the LON.

In Figure 22, the CIP is located at a distance 6 ft.-10 in. from the tip of the end-treatment. At this point, the height of the end-treatment (essentially 6 in.) matches the height of the FDOT Type-F concrete curb. It has been established through computer simulation and physical testing that typical 820C vehicles are capable of mounting and traversing 6 in. curbs. Selecting the CIP for test 2-34 to coincide with this height therefore reasonably ensured that the front right tire of the 820C would mount and traverse the end-treatment, resulting in a critical condition in terms of vehicle roll angle and stability. In fact, later full-scale crash tests confirmed this to be the case. In the 2-34 full-scale crash-test, the right-front tire mounted the end-treatment at the impact point and traversed its width. This, in turn, resulted in the left-front tire following a trajectory up and over essentially the tallest part of the end-treatment, producing a worst case scenario in regard to *potential* for vehicle rollover. Vehicle rollover did **not** occur during the physical crash test.

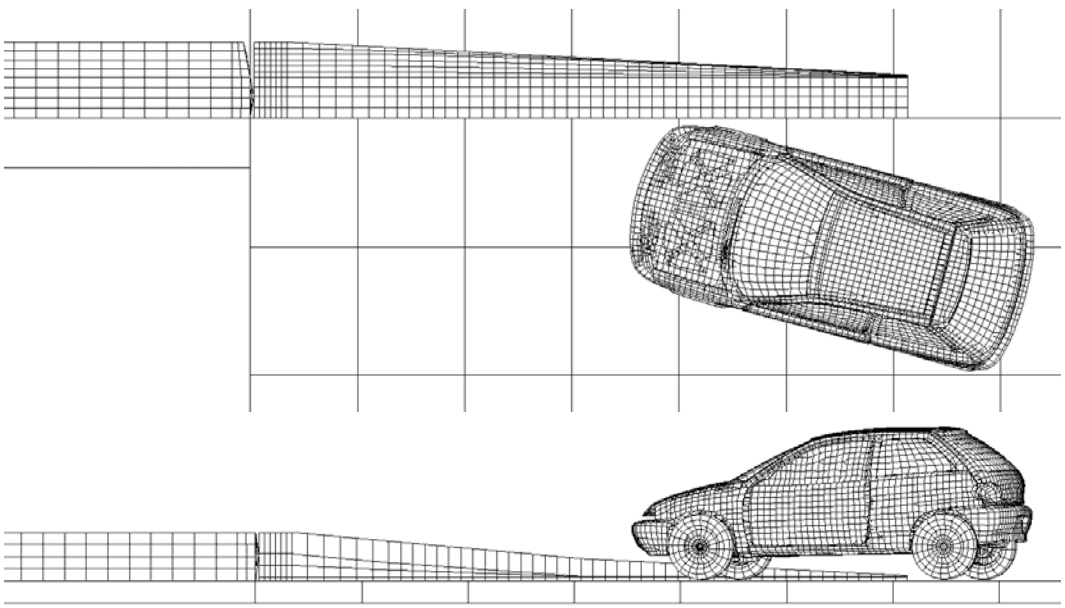


Figure 22. Finite element model of test 2-34 (820 kg car, 15-deg. angle)

In Figure 23, the model corresponding to NCHRP 350 test condition 2-35 is shown. Test 2-35 involves a 20-degree oblique impact of a 2000P vehicle striking the end-treatment at the beginning of the LON. With regard to test 2-35, NCHRP Report 350 states:

> Test 35 is intended primarily to evaluate the ability of the device to contain and redirect (structural adequacy criteria) the 2000P vehicle within vehicle trajectory criteria at the beginning of the LON.

As noted earlier, given that 18 in. was previously determined (during an earlier study) to be the minimum barrier height capable of redirecting a 2000P vehicle, there is no expectation that any portion of an end-treatment less than 18 in. in height will be capable of redirecting this same vehicle. Consequently, no part of the end-treatment is considered to contribute to the LON of barrier that is required to protect a particular work-zone. Therefore, the beginning of the LON coincides with the end of the end-treatment and the beginning of the low-profile barrier segments. This same location then becomes the point of impact for test 2-35 (Figure 23).

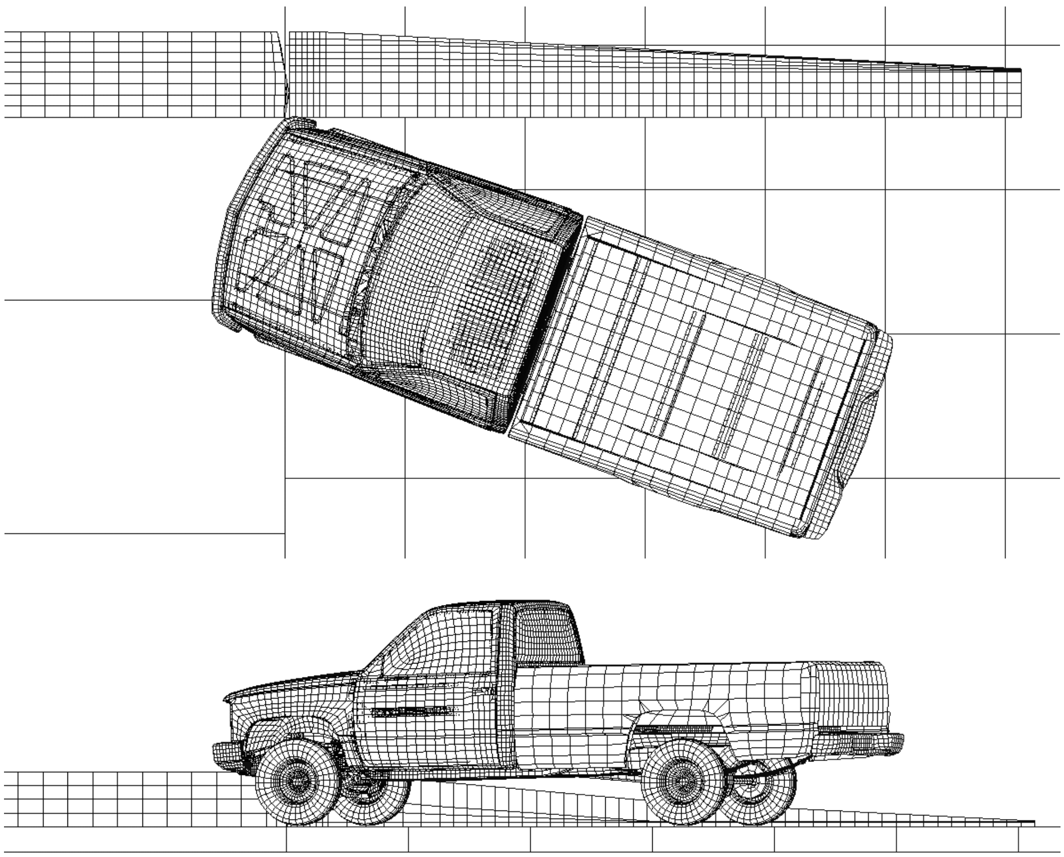


Figure 23. Finite element model of test 2-35 (2000 kg truck, 20-deg. angle)

In Figure 24, the model corresponding to NCHRP 350 test condition 2-39 is shown. Test 2-39 involves a reverse-angle 20-degree oblique impact of a 2000P vehicle striking the end-treatment at the location midway between the beginning and end of the end-treatment. Results obtained from the models described above, as well as additional simulations that were conducted (e.g., to consider variations in frictional coefficients), indicated that the tapered end-treatment concept had good potential for passing the required matrix of NCHRP Report 350 crash tests.

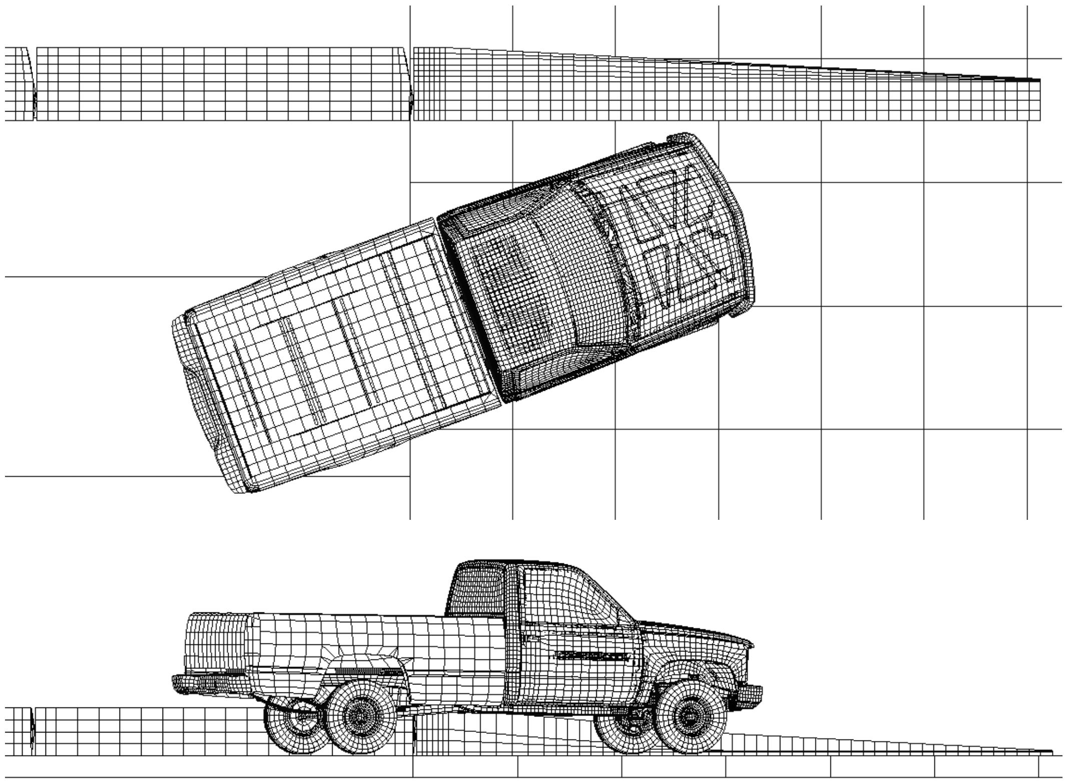


Figure 24. Finite element model of test 2-39 (2000 kg truck, 20-deg. reverse angle)

4.4 Structural design

Given that the end-treatment is only 2 in. tall (thick) at its tip, constructing the entire 20 ft. long device using solely reinforced concrete was not practical. Moreover, a 20 ft. long end-treatment would be unwieldy to handle, transport, and install. For these reasons, the device was designed as two separate structural components (Figure 25) that are joined together in the field during installation. One component (segment) of the end-treatment is constructed from reinforced concrete and is 12 ft. in length (the same length as the low-profile barrier segments), while the second component is fabricated from structural steel and is 8 ft. in length. The approach of dividing the system into two modular components also has the advantage that if one portion is damaged during a collision, but the other is not, only the damaged component need be replaced. Dynamic forces used to design the connection between the steel and concrete segments were determined by processing and interpreting data obtained from finite element impact simulations. The vertical slope of the end-treatment changes at the connection point between the concrete and steel sub-components.

In order to permit the end-treatment to be attached to either the key or keyway end of a low-profile barrier segment, the end-treatment geometry was altered slightly from that used in the finite element simulations so that the segments (concrete and steel) are essentially symmetric about their longitudinal axes. The only portion of the end-treatment that is not symmetric about the longitudinal axis is the tall-end of the concrete segment where the end-treatment attaches to low-profile barrier segments. At this location, an innovative connection scheme was developed that makes the end-treatment reversible. That is, the same end-treatment system can be attached to either the upstream or downstream (key or keyway) ends of a low-profile barrier segment simply by changing the connection hardware that is used.

In Figure 26, an example short installation is illustrated in which end-treatments have been attached to both ends of a single low-profile barrier segment. In this figure, the impact faces of the end-treatment segments have been aligned with the impact face of the barrier segment. Additional details of the connection systems at the keyway and key ends of the low-profile barrier segment are presented in Figures 27 and 28, respectively. In Appendix A of this report, a complete set of highly detailed end-treatment fabrication and installation drawings are provided.

In addition to designing the concrete and steel end-treatment segments to resist impact loads associated with vehicle collisions, other considerations were also taken into account. For the 12 ft. concrete segment, dynamic vertical handling loads were considered when selecting the internal longitudinal reinforcing steel. For the steel segment, the spacing and quantity of vertical internal stiffener plates were based partially (per suggestion by FDOT) on the anticipation that heavy trucks will likely drive over this portion of the end-treatment in congested work zones.

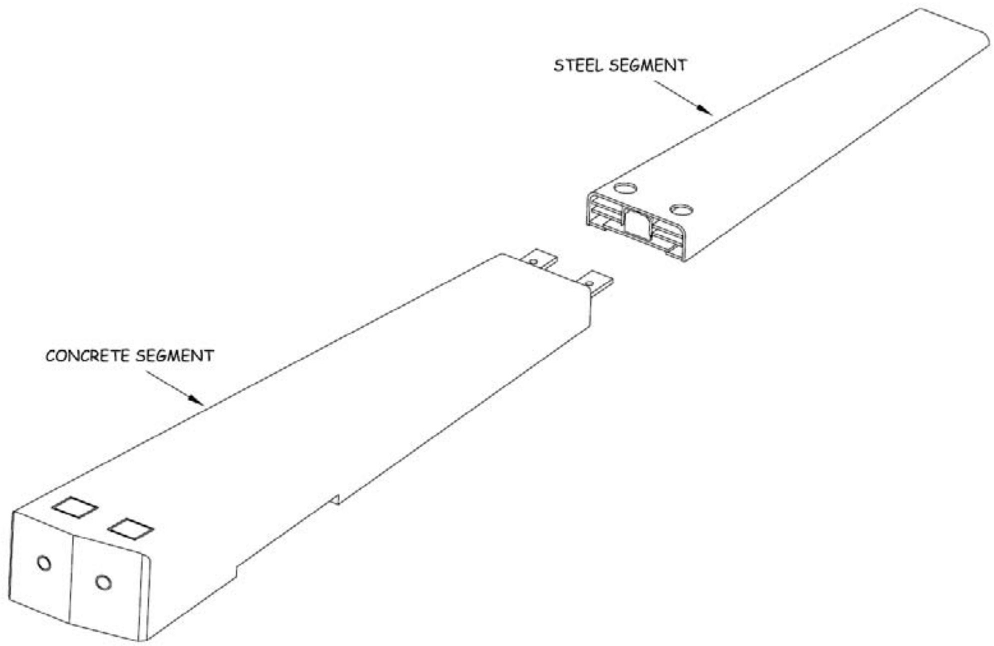


Figure 25. End-treatment composed of reinforced concrete and structural steel components

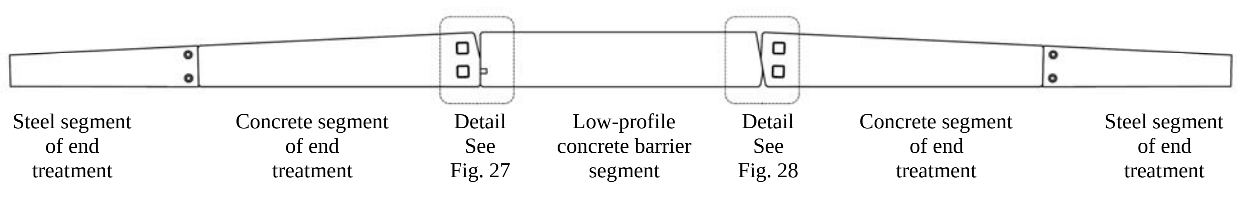


Figure 26. End-treatments connected to both ends of a single low-profile barrier segment

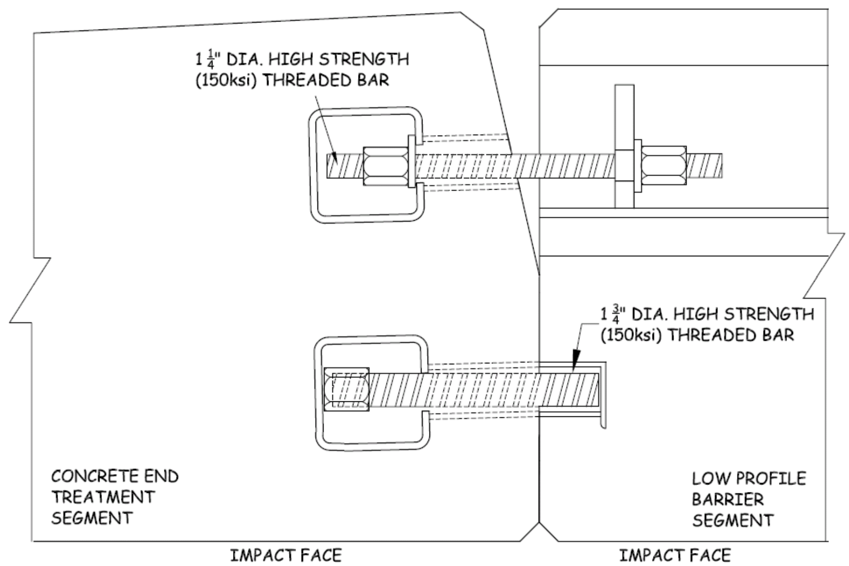


Figure 27. Connection of the concrete end-treatment segment to the keyway-end of a concrete low-profile barrier segment

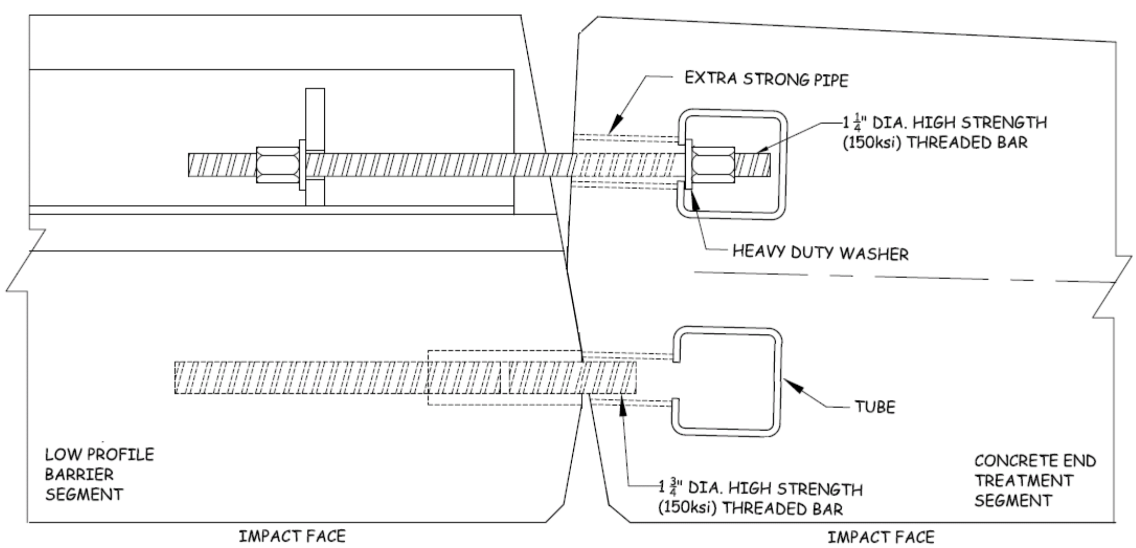


Figure 28. Connection of the concrete end-treatment segment to the key-end of a concrete low-profile barrier segment

5. FULL-SCALE CRASH TESTS: PERFORMANCE VALIDATION

Although finite element impact simulation is a powerful development and design tool, full-scale crash testing in accordance with the requirements of NCHRP Report 350 is still necessary to demonstrate the performance of the new end-treatment. Since end-treatment is intended for use near work-zones where the speed limit is 45 mph or less, NCHRP Report 350 test level 2 testing was performed.

E-Tech Testing Services, Inc. of Rocklin, California was contracted to carry out the required series of seven NCHRP Report 350 tests (tests 2-30, 2-31, 2-32, 2-33, 2-34, 2-35, and 2-39). However, Florida-based fabricators were chosen to manufacture the crash test-articles so as to ensure that the fabrication capabilities needed to produce the end-treatment were available within the state. Dixie Metal Products, Inc. of Ocala, Florida was contracted to fabricate the 8 ft. steel end-treatment segment and the internal structural steel components of the 12 ft. concrete segment. Seminole Precast Manufacturing, Inc. of DeBary Florida was contracted to cast the concrete segments. The segments were then shipped to E-Tech Testing Services in California for crash testing.

In tests 2-30 through 2-35, the end-treatment was attached to a series of fifteen low-profile barrier segments and in test 2-39, it was attached to a series of eight low-profile barrier segments. The E-Tech test site (Figure 29) is situated on a dusty, abandoned runway that has an aged asphalt concrete chip seal surface condition thought to be a worst case scenario for in-field use of the combined end-treatment-and-barrier system. Neither the end-treatment nor the barrier segments were fastened to the road surface in any manner for testing. A pulley system was used to tow the test vehicle up to the test speed and impact angle. The steering mechanism was disengaged just prior to impact, constituting a hands-off test condition. High-speed cameras recorded the tests from different angles. Instrumentation in the vehicle provided time histories of vehicle accelerations to estimate the forces on occupants. Post-test data reduction determined if the barrier passed the structural adequacy, re-direction, and occupant safety criteria.

Figure 29. End-treatment attached to Florida low-profile barrier prior to crash-testing

Tests were conducted (Figures 30 - 36) over an approximately six-week period spanning from late April 2008 to mid June 2008. The end-treatment successfully passed all of the required tests with adequate vehicle redirection (where appropriate) and no incidents of vehicle rollover. Occupant risk measures were all within acceptable limits set forth by NCHRP Report 350. It is also worth noting that a single end-treatment test-article was used for the entire series of crash tests, with only minor cosmetic damage being evident at the completion of testing. Hence, it may be concluded that the newly developed system possesses a reasonable level of durability in addition to adequacy of impact performance.

E-Tech Testing has issued a final report certifying that the end-treatment passed the NCHRP Report 350 test level 2 test requirements. A copy of that report is included in Appendix B. The reader is referred to the E-Tech report for further details regarding test set up, data analysis, and photos of pre-impact and post-impact conditions.

Figure 30. Full-scale crash test 2-30

Figure 31. Full-scale crash test 2-31

Figure 32. Full-scale crash test 2-32

Figure 33. Full-scale crash test 2-33

Figure 34. Full-scale crash test 2-34

Figure 35. Full-scale crash test 2-35

Figure 36. Full-scale crash test 2-39

6. CONCLUSION

In this study, vehicle and barrier finite element models (developed during an earlier study) have been calibrated using results from full-scale crash testing. The calibrated models have then been used to conduct parametric studies for the purposes of: 1) determining the relationship between vehicle impact speed and lateral barrier deflection, and 2) assessing the performance of the barrier in various drop-off zone configurations. Based on the computed relationship between vehicle impact speed and lateral barrier deflection, if conservative estimates of barrier-to-roadway friction are made, reducing the speed limit in a work zone from 45 mph to 30 mph reduces the effective-width of the Florida low-profile barrier from 37.1 in. to 36.1 in. Based on results obtained from separate simulations, the minimum required lateral deflection space that provides adequate barrier performance in drop-off zone applications is 6 in. for an impact speed of 45 mph.

In addition, a new crashworthy end-treatment—to be used in conjunction with the Florida low-profile barrier system—has been successfully developed. The end-treatment is 20 ft. long, is composed of a 12 ft. long reinforced concrete segment and an 8 ft. steel segment, and tapers from 18 in. to 2 in. in height. An innovative connection system and a nearly symmetric shape make the end-treatment reversible. This reversibility permits the end-treatment to be attached to either the key or keyway ends of low-profile barrier segments. Neither the end-treatment nor the low-profile barrier to which it attaches require any mechanical anchorage to the roadway surface. Finite element impact analyses were used to establish the geometric shape of the end-treatment and to quantify design forces. Subsequently, the end-treatment was structurally-designed, fabricated, and subjected to a series of seven full-scale crash tests per the test level 2 requirements of NCHRP Report 350. Crash tests involving both a small car (820kg) and a full-size pickup truck (2000 kg) were successfully passed.

REFERENCES

Beason, W.L. (1992), *Development of an End Treatment for a Low-Profile Concrete Barrier*, Research Report 1949-2, Texas Transportation Institute, The Texas A&M University System, College Station, Texas.

Beason, W.L., Menges, W.L., and Ivey, D.L. (1998), *Compliance Testing of an End Treatment for the Low-Profile Concrete Barrier*, Research Report 1403-S, Texas Transportation Institute, The Texas A&M University System, College Station, Texas.

Consolazio, G.R., Chung, J.H., Gurley, K.R. (2003), "Impact Simulation and Full Scale Crash Testing of a Low Profile Concrete Work Zone Barrier", *Computers and Structures*, Vol. 81, No.13, pp. 1359-1374.

Consolazio, G.R., Gurley, K.R., Ellis, R., Wilkes, J. (2003), *Temporary Low Profile Barrier for Roadside Safety : Phase II*, Structures Research Report No. 827-3, Engineering and Industrial Experiment Station, University of Florida, Gainesville, Florida.

Ellis, R., Consolazio, G.R., Gurley, K.R., Chug, J.H. (2001), *Managing the Maintenance of Traffic through FDOT Work Zones*, Structures Research Report No. 661-1, Engineering and Industrial Experiment Station, University of Florida, Gainesville, Florida.

Guidry, T.R., and Beason, W. L. (1992), "Development of a Low-Profile Portable Concrete Barrier", *Transportation Research Record No. 1367 : Development and Evaluation of Roadside Safety Features*, Transportation Research Board.

LS-DYNA (2003), *LS-DYNA Keyword User's Manual: Version 970*, Livermore Software Technology Corporation, Livermore, CA.

NCHRP (1993), *NCHRP Report 350 : Recommended Procedures for the Safety Performance Evaluation of Highway Features*, Transportation Research Board, National Cooperative Highway Research Program, Washington, D.C.

APPENDIX A

TAPERED END-TREATMENT FOR LOW-PROFILE BARRIER WALL
(END-TREATMENT DESIGN DRAWINGS)

UNIVERSITY OF FLORIDA
TAPERED END TREATMENT FOR LOW-PROFILE BARRIER WALL

GENERAL NOTES:

1. CONCRETE
   A. CONCRETE MIX:
      fc'i = 3,000 psi AT FORM REMOVAL
      f'c = 5,000 psi AT 28 DAYS.

   B. CURING SHALL BE IN ACCORDANCE WITH CURRENT FLORIDA DOT STANDARDS.

   C. NEITHER TRANSPORT NOR INSTALLATION OF BARRIER SEGMENTS SHALL TAKE PLACE BEFORE THE 28 DAY CONCRETE STRENGTH HAS BEEN ACHIEVED.

2. ALL REBAR SHALL BE A615, GR60.

3. ALL STRUCTURAL STEEL (EXCEPT AS NOTED BELOW) SHALL BE A572 GRADE 50

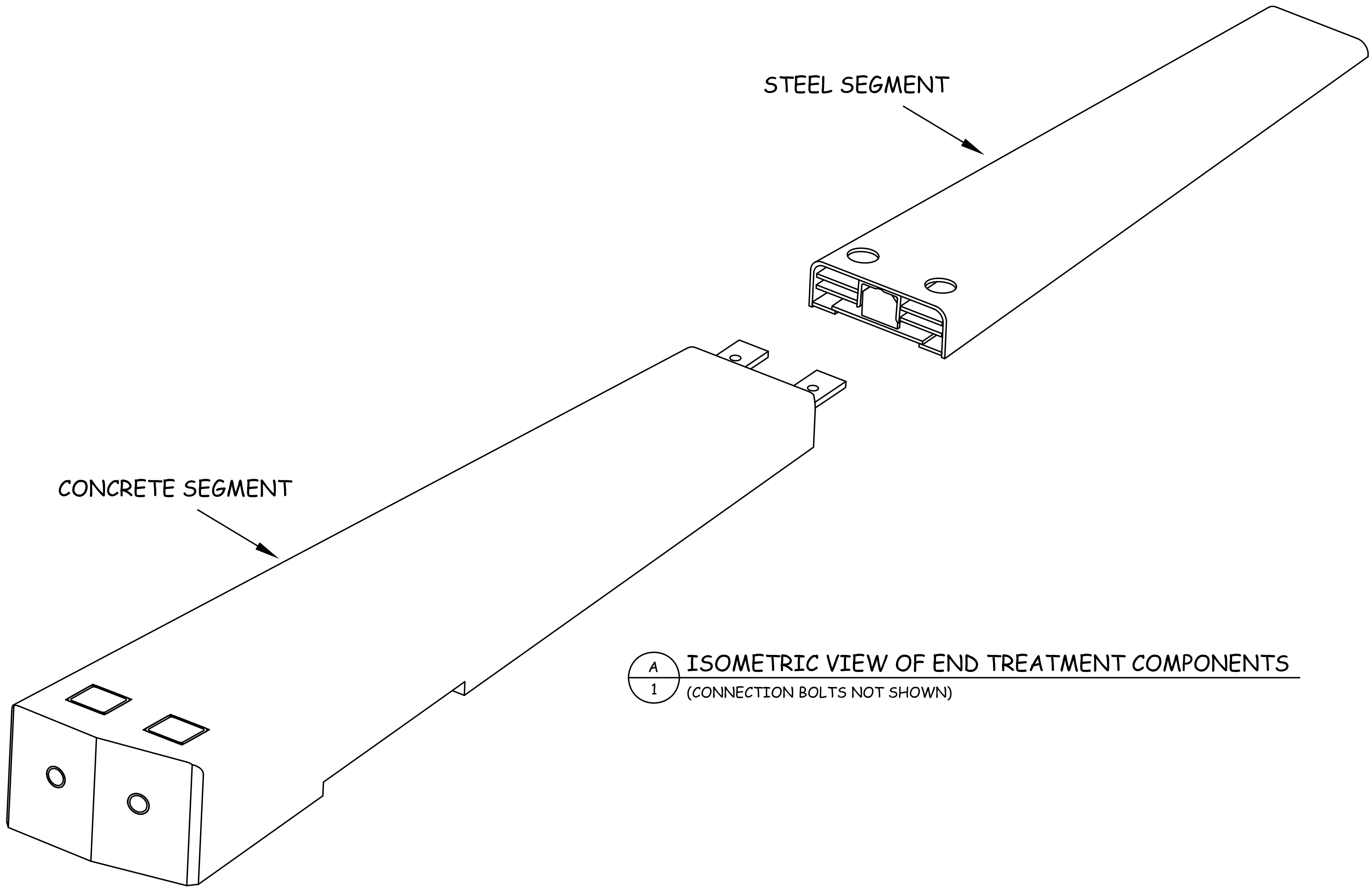
4. ALL STRUCTURAL STEEL TUBE SHALL BE A500 GRADE B OR C

5. ALL STRUCTURAL STEEL PIPE SHALL BE A53 GRADE B

6. FABRICATION OF THE CONCRETE UNITS SHALL CONFORM TO THE REQUIREMENTS OF ACI 318-02.

7. MANUFACTURERS OF CONCRETE UNITS SHALL CONFORM TO THE CURRENT FLORIDA DEPARTMENT OF TRANSPORTATION REQUIREMENTS FOR QUALITY CONTROL. CONTACT THE FLORIDA DEPARTMENT OF TRANSPORTATION, STATE MATERIALS OFFICE FOR INFORMATION ON CURRENT REQUIREMENTS (352-955-6683).

UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL

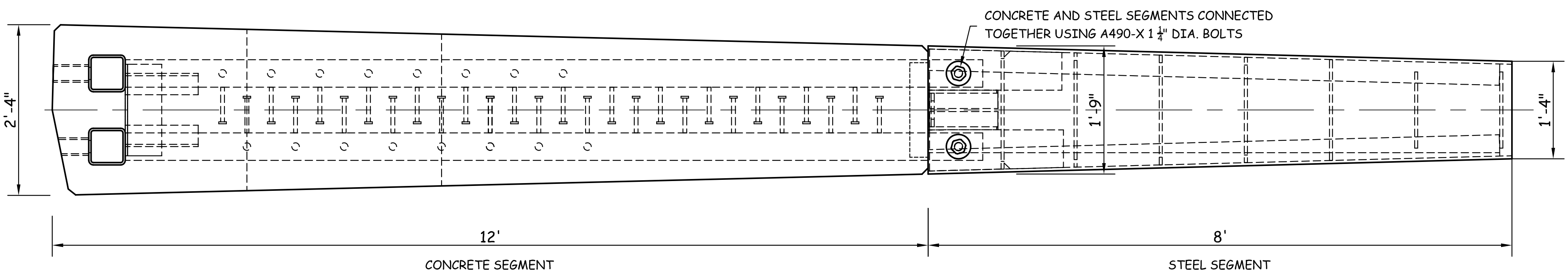


A/1 ISOMETRIC VIEW OF END TREATMENT COMPONENTS
(CONNECTION BOLTS NOT SHOWN)

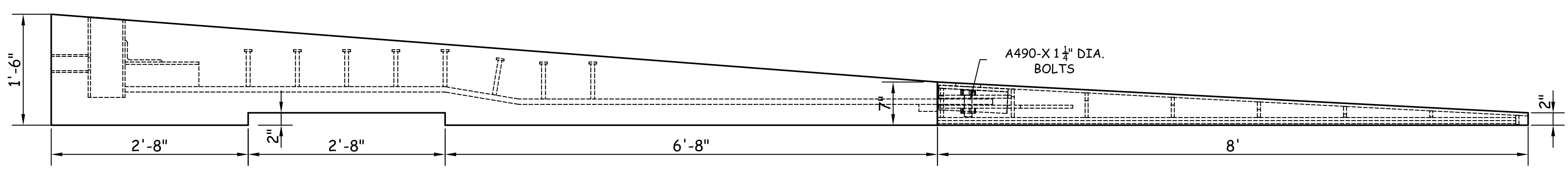
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 1

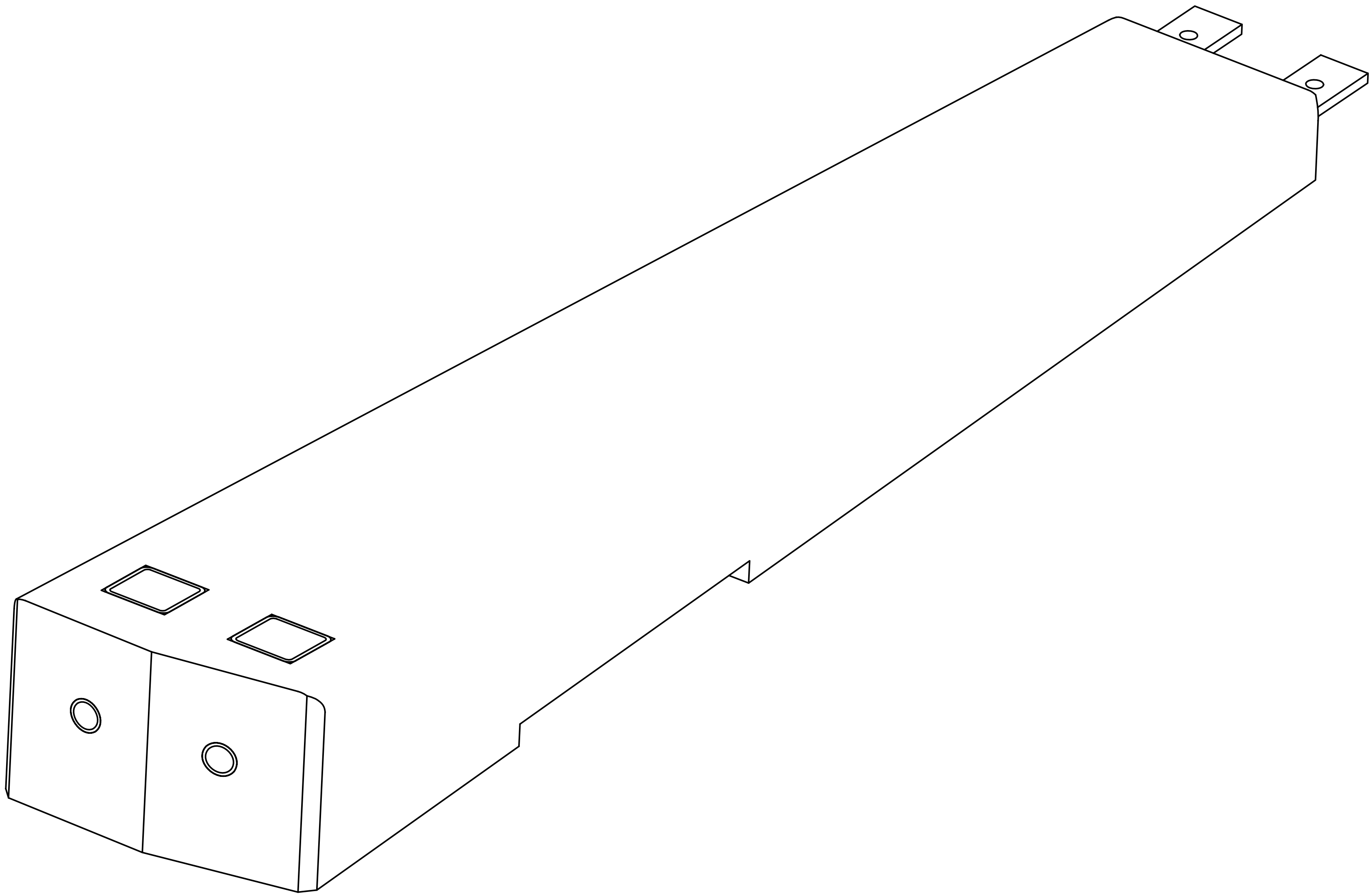


A/2 PLAN VIEW



B/2 ELEVATION VIEW

UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 2

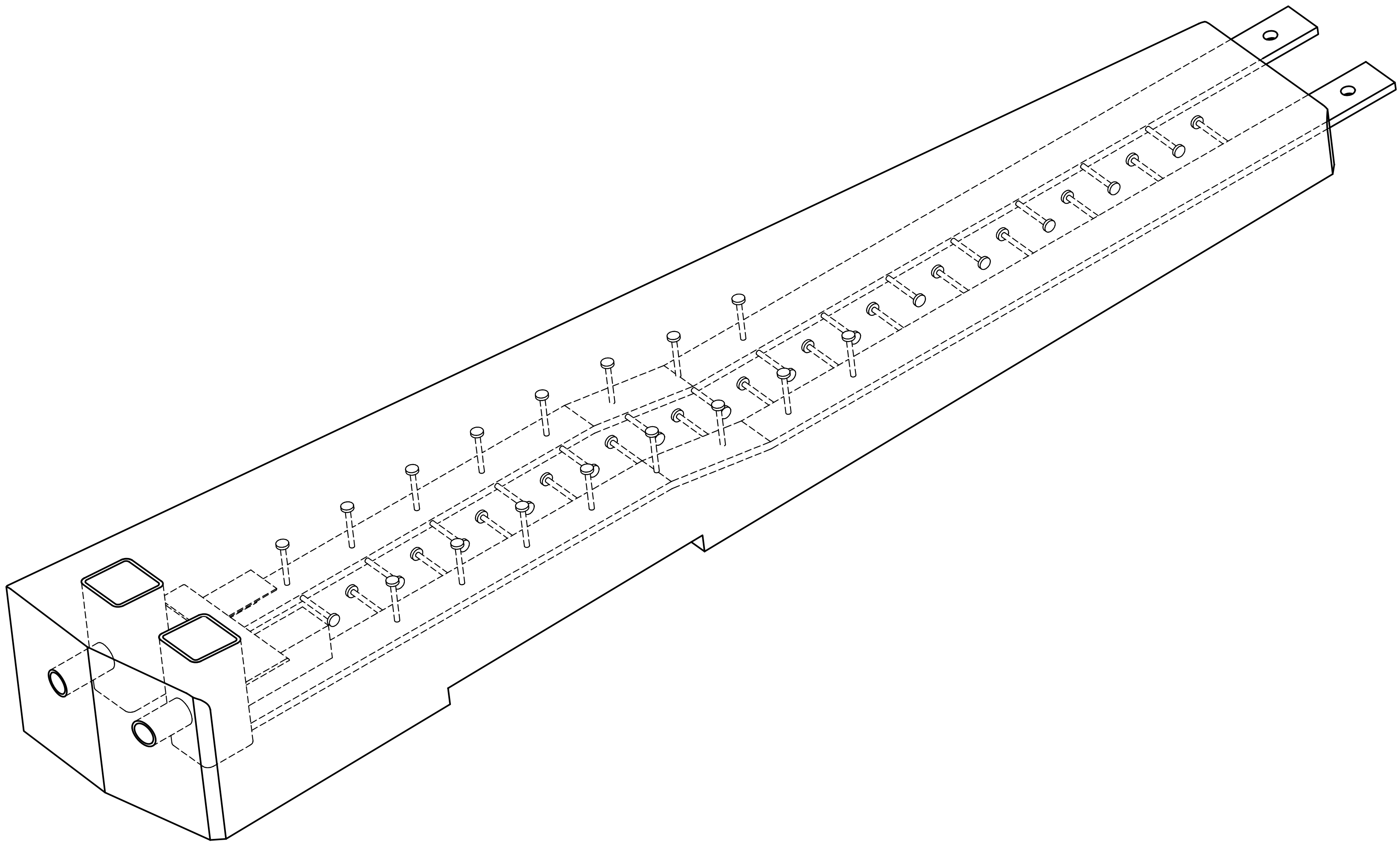


A/3 ISOMETRIC VIEW OF CONCRETE SEGMENT

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 3



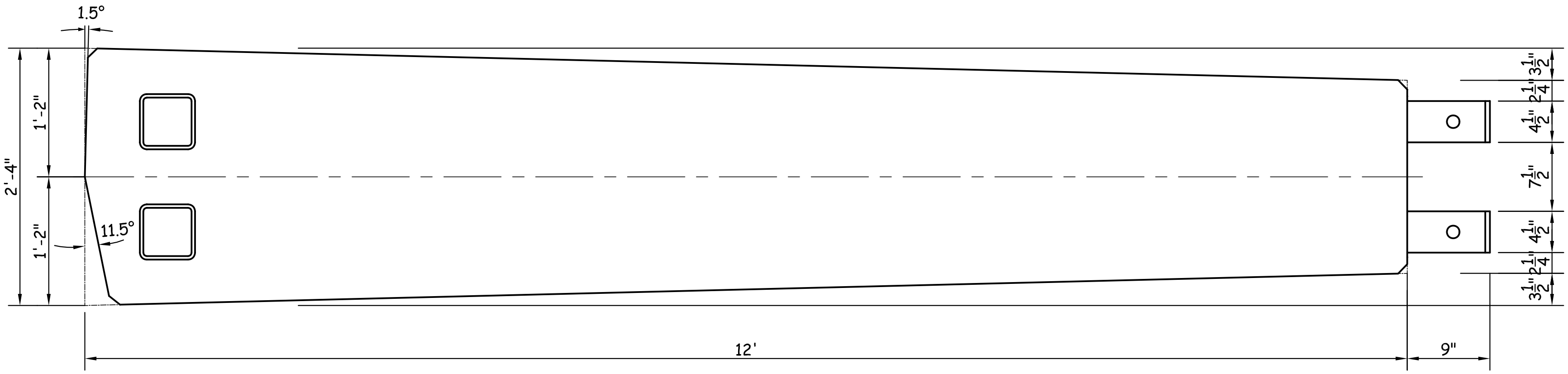
(A/4) ISOMETRIC VIEW OF INTERNAL COMPONENTS OF CONCRETE SEGMENT

(REINFORCING STEEL OMITTED FOR CLARITY)

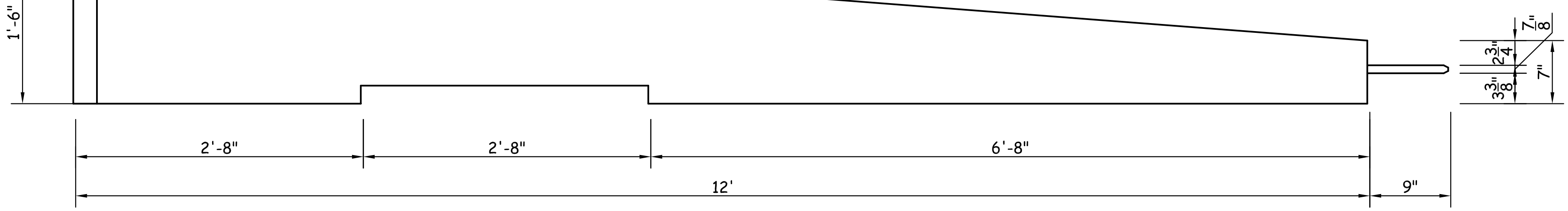
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 4



A/5 PLAN VIEW OF CONCRETE SEGMENT

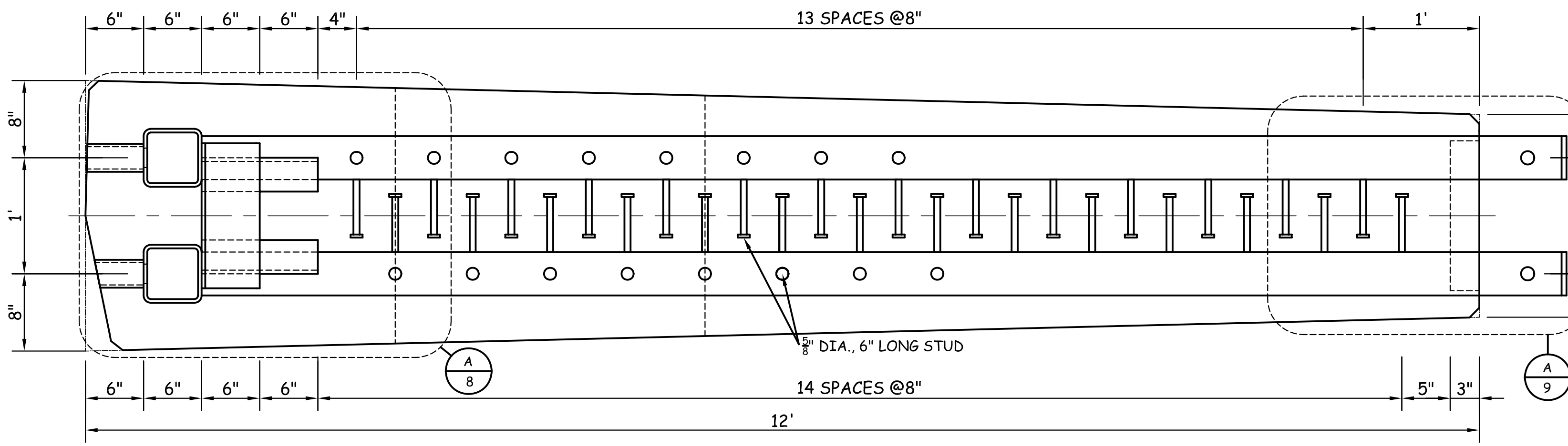


B/5 ELEVATION VIEW OF CONCRETE SEGMENT

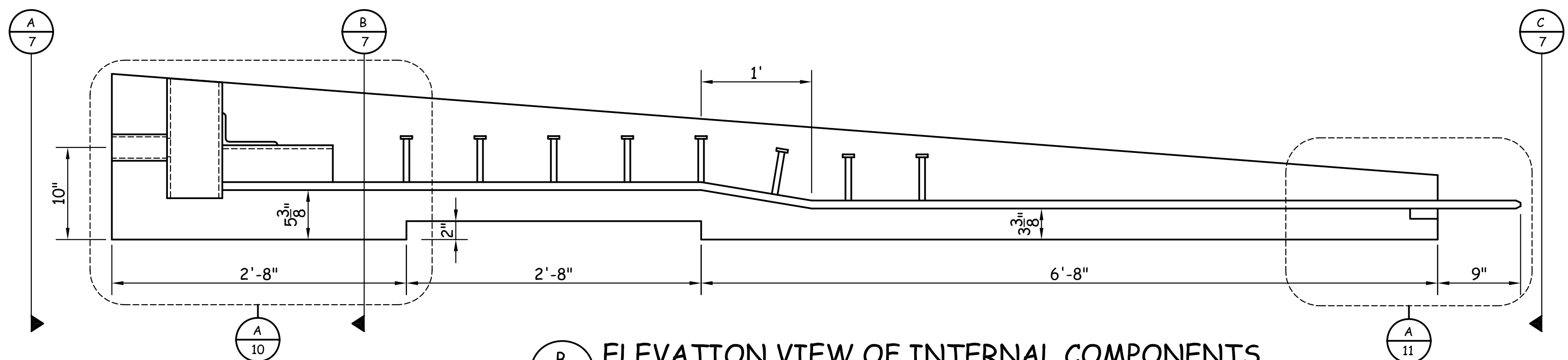
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 5



A 6 PLAN VIEW OF INTERNAL COMPONENTS
(REINFORCING STEEL OMITTED FOR CLARITY)

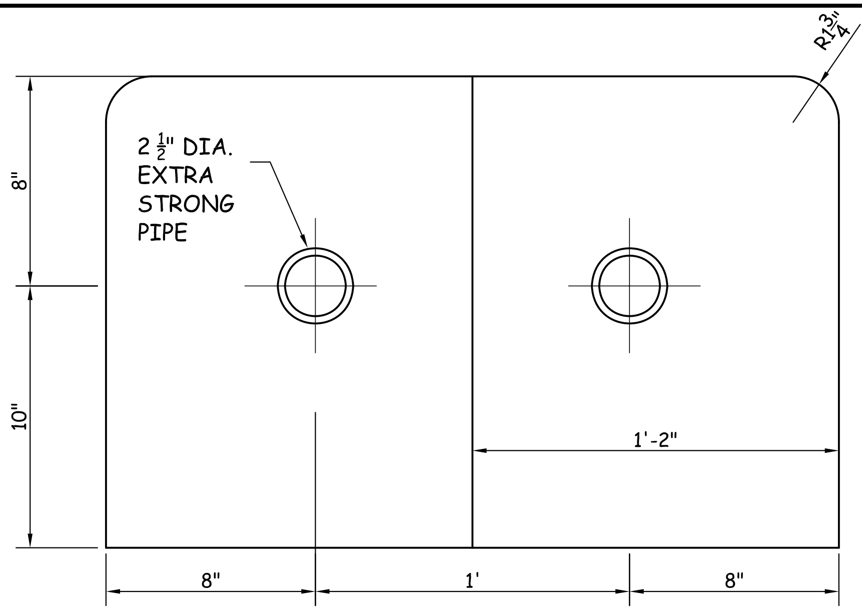


B 6 ELEVATION VIEW OF INTERNAL COMPONENTS
(REINFORCING STEEL OMITTED FOR CLARITY)

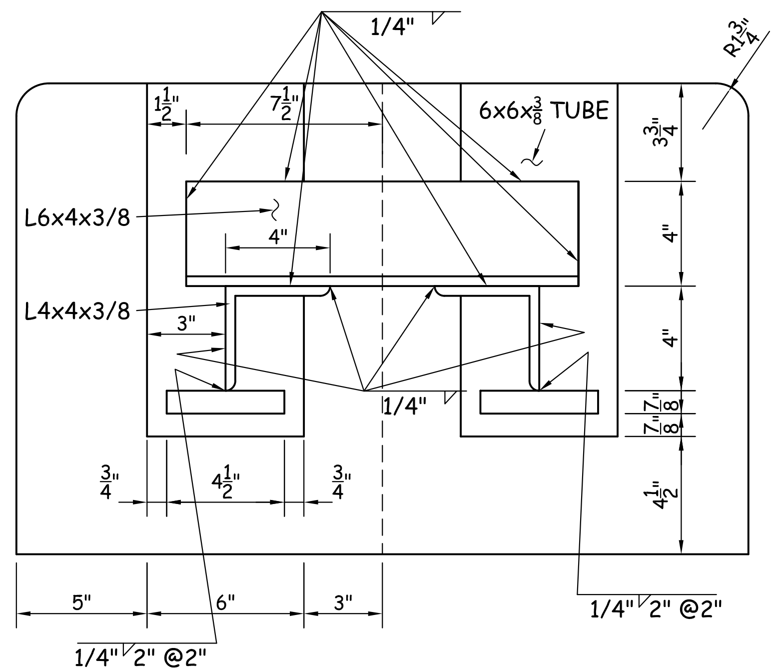
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

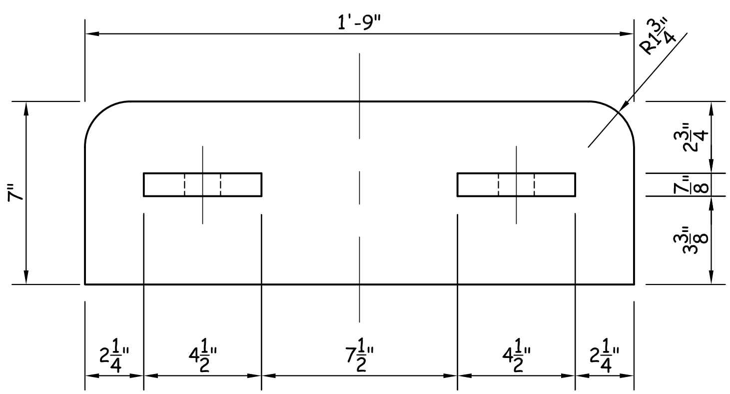
SHEET NO. 6



A/7 END VIEW



B/7 SECTION VIEW

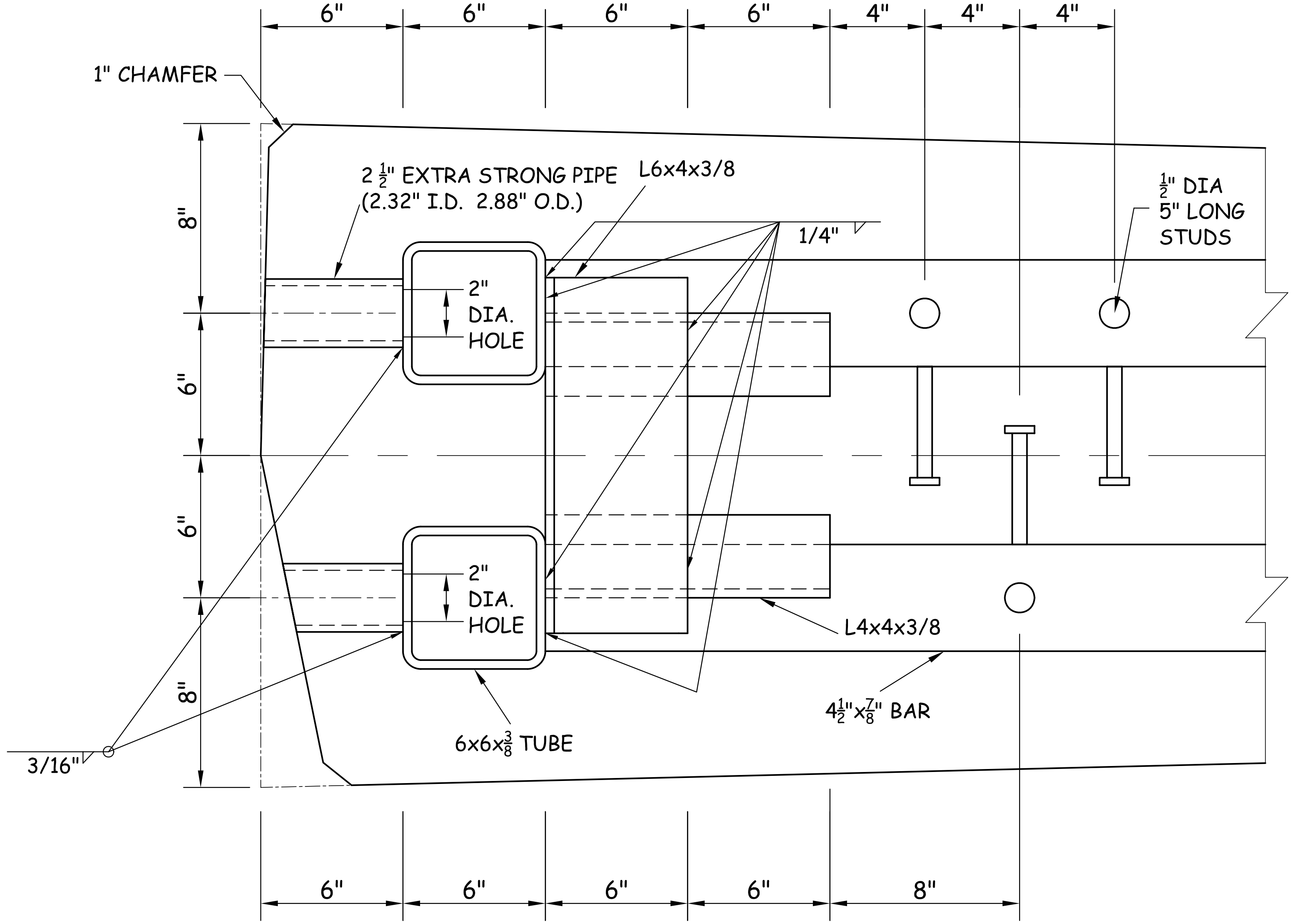


C/7 END VIEW

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 7

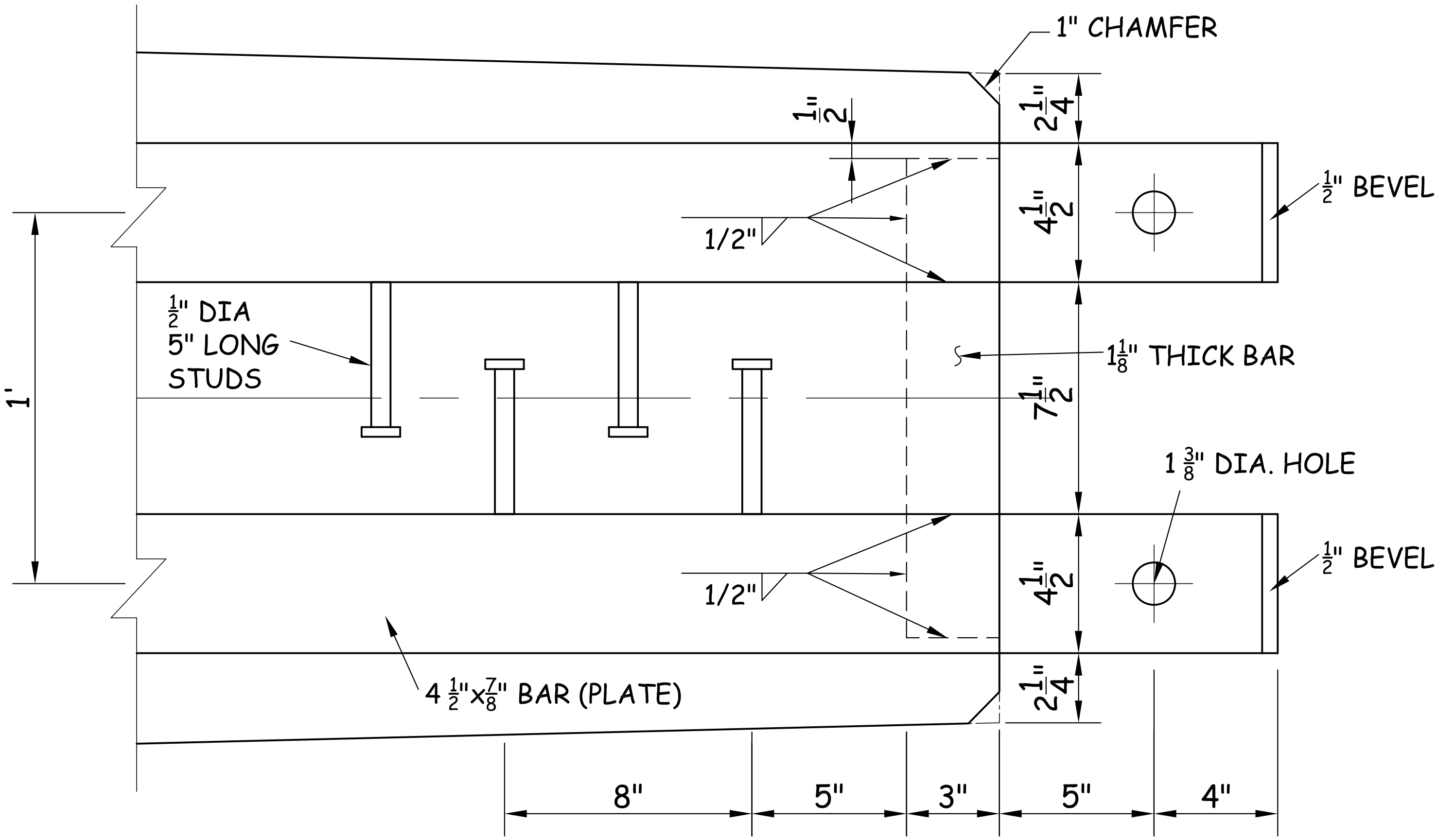


A/8 PLAN VIEW OF CONCRETE SEGMENT END
(REINFORCING STEEL OMITTED FOR CLARITY)

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 8



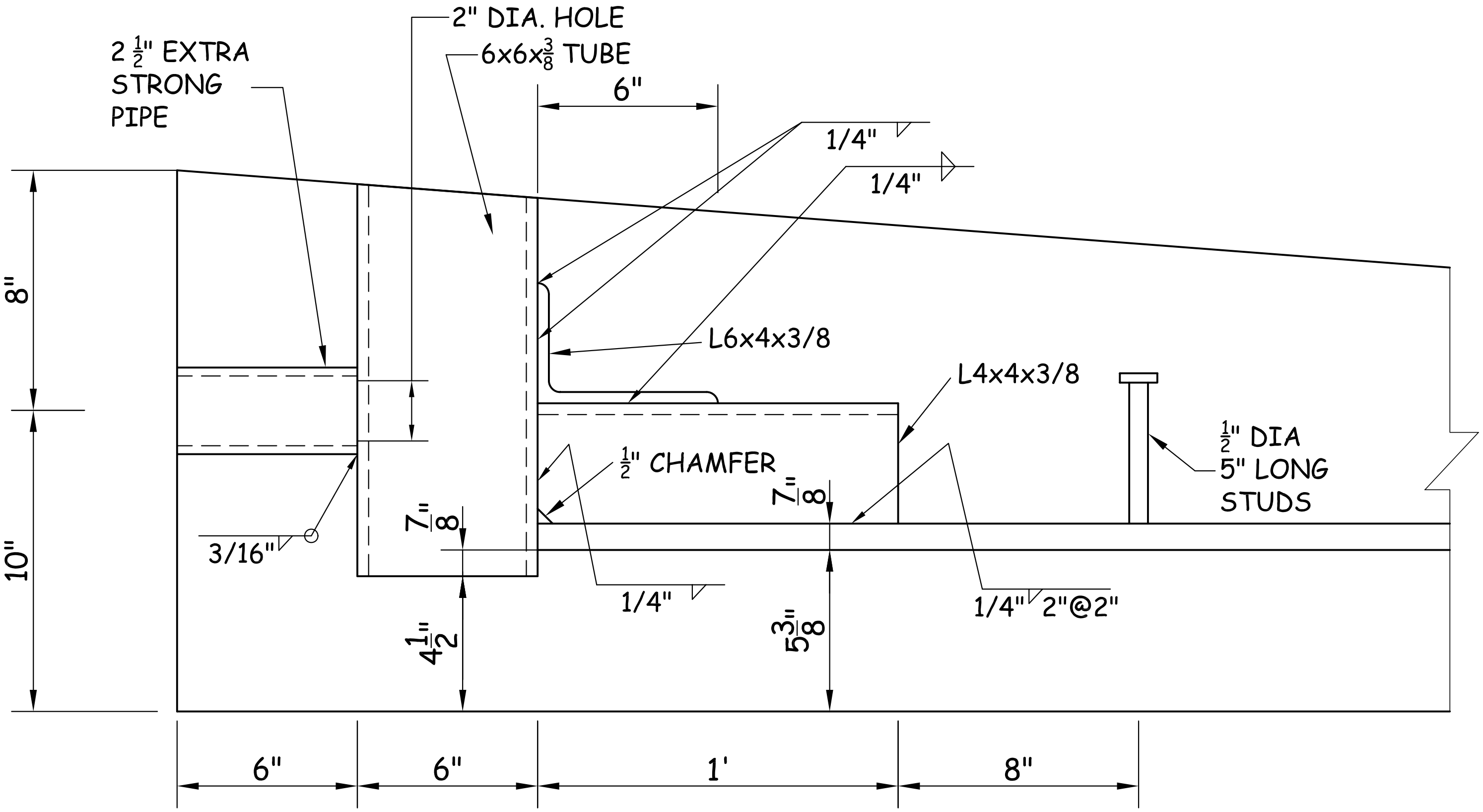
A/9 PLAN VIEW AT CONCRETE SEGMENT END

(REINFORCING STEEL OMITTED FOR CLARITY)

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 9

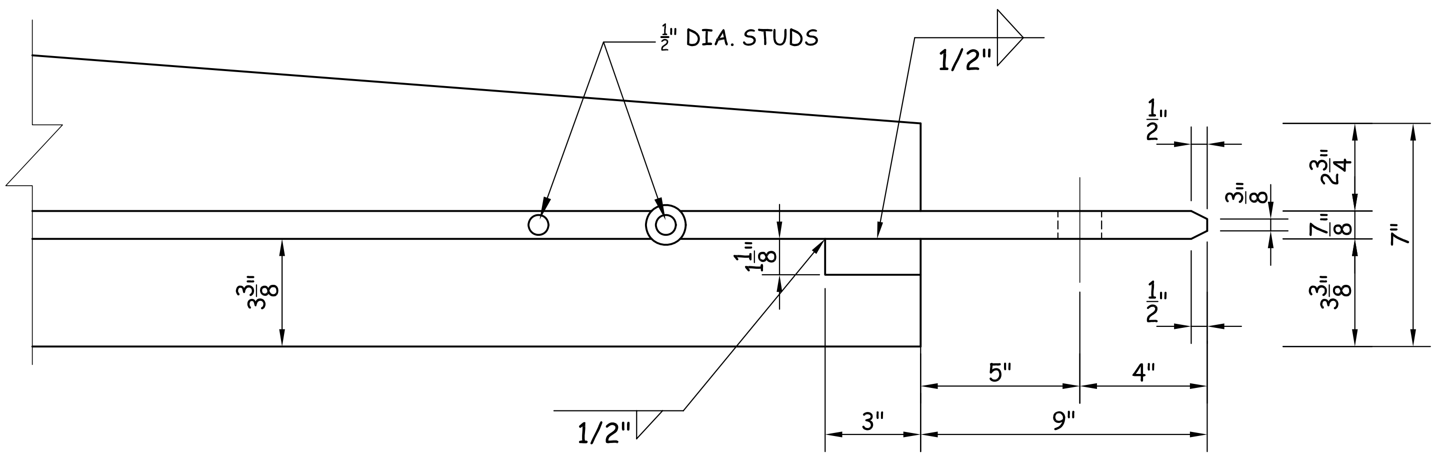


A
10

SECTION VIEW OF CONCRETE SEGMENT END

(REINFORCING STEEL OMITTED FOR CLARITY)

UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 10



SECTION VIEW OF CONCRETE SEGMENT END

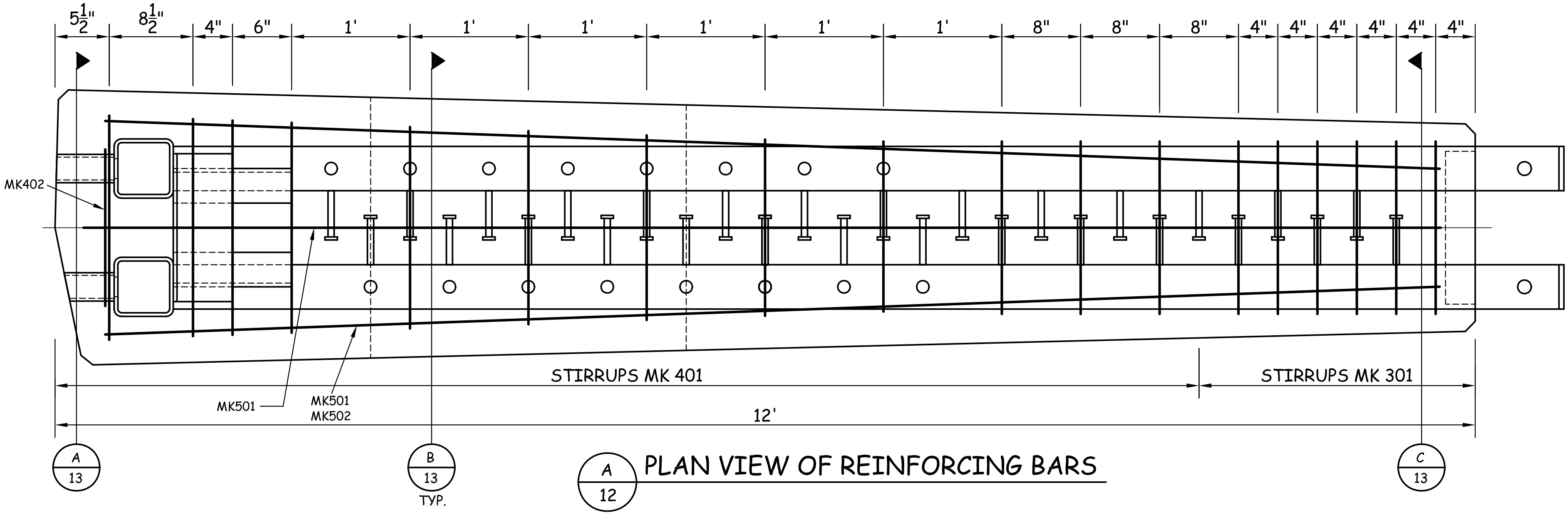
A / 11

(REINFORCING STEEL OMITTED FOR CLARITY)

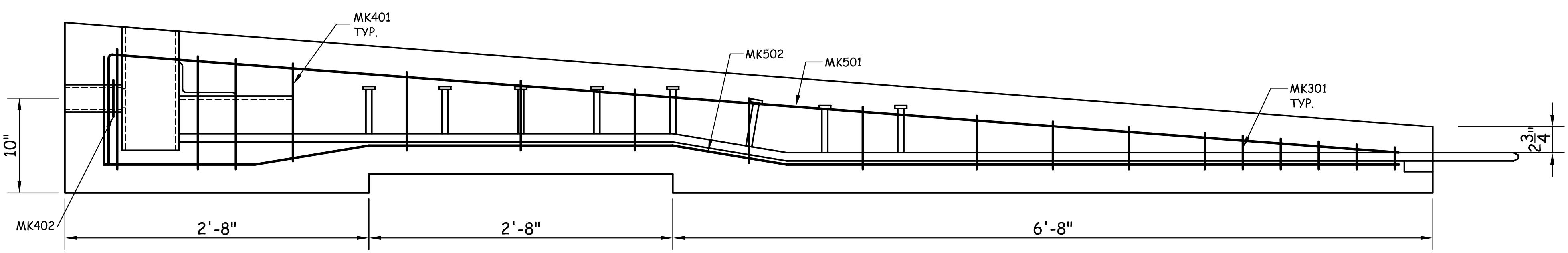
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 11



A / 12 PLAN VIEW OF REINFORCING BARS

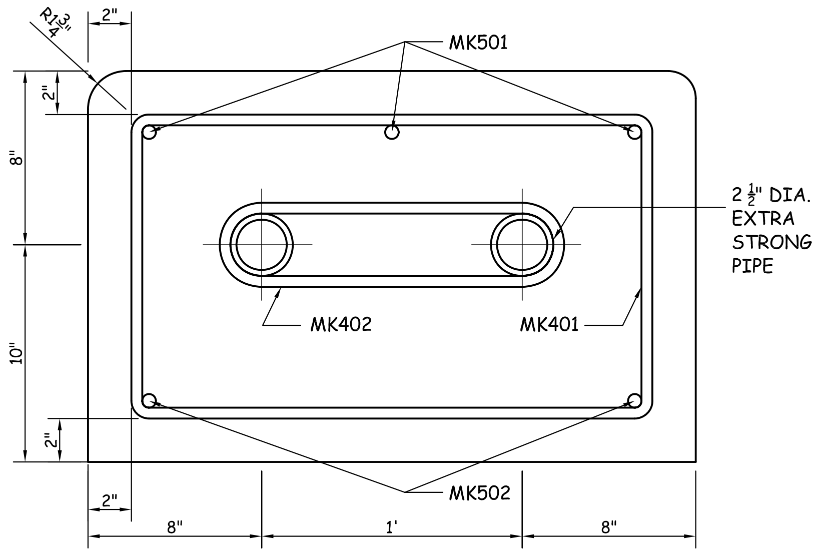


B / 12 ELEVATION VIEW OF REINFORCING BARS

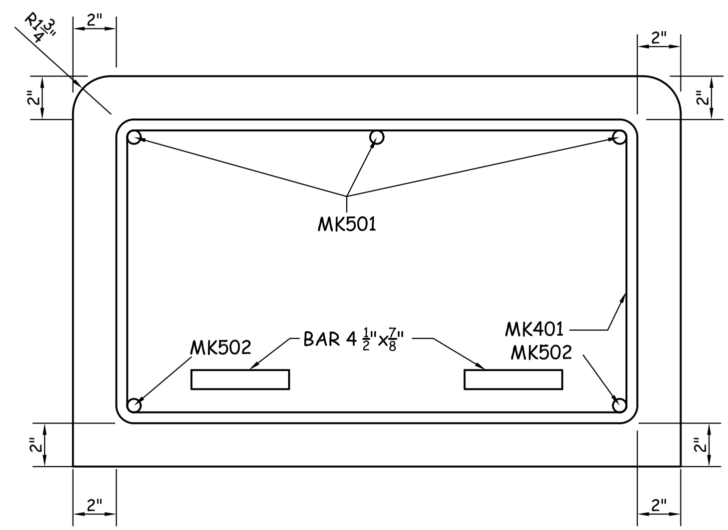
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

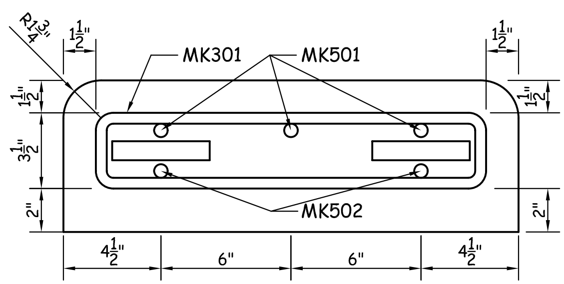
SHEET NO. 12



A 13 SECTION



B 13 SECTION



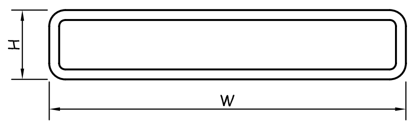
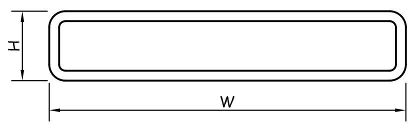
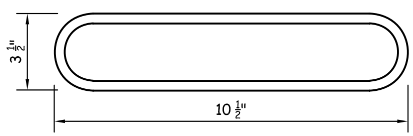
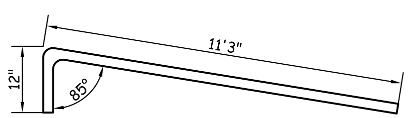
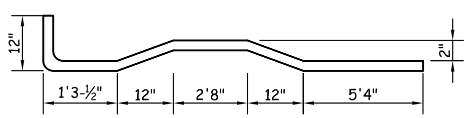
C 13 SECTION

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 13

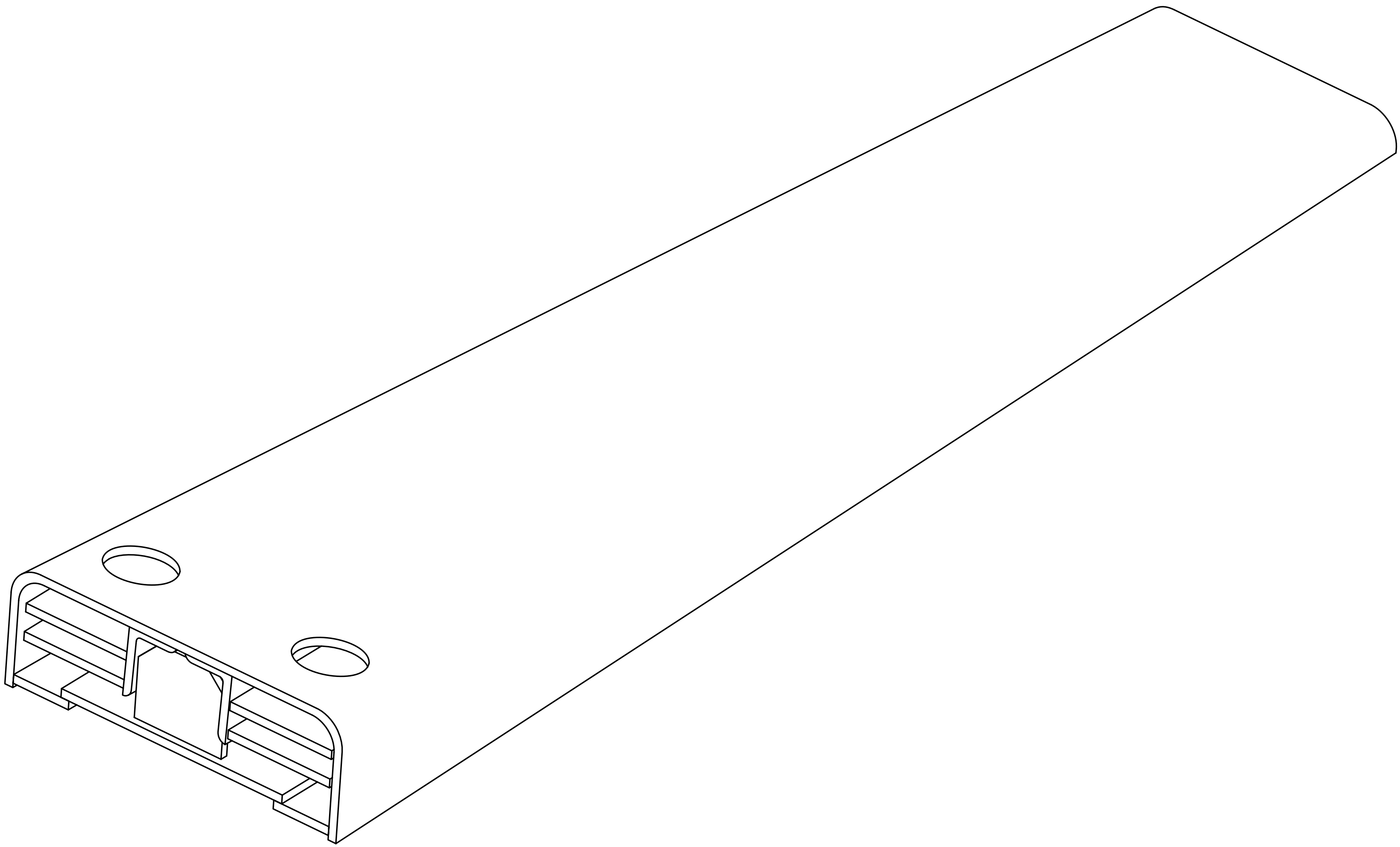
REINFORCING BAR BEND SCHEDULE

BAR SIZE	DETAILS	MARK NO.	PCS /UNIT
#3	 H: VARIES FROM 3 ½" TO 5 ¼" W: VARIES FROM 18" TO 19 ¼"	MK301	6
#4	 H: VARIES FROM 5 ½" TO 14" W: VARIES FROM 18 ½" TO 24"	MK401	12
#4		MK402	1
#5		MK501	3
#5		MK502	2

UNIVERSITY OF FLORIDA

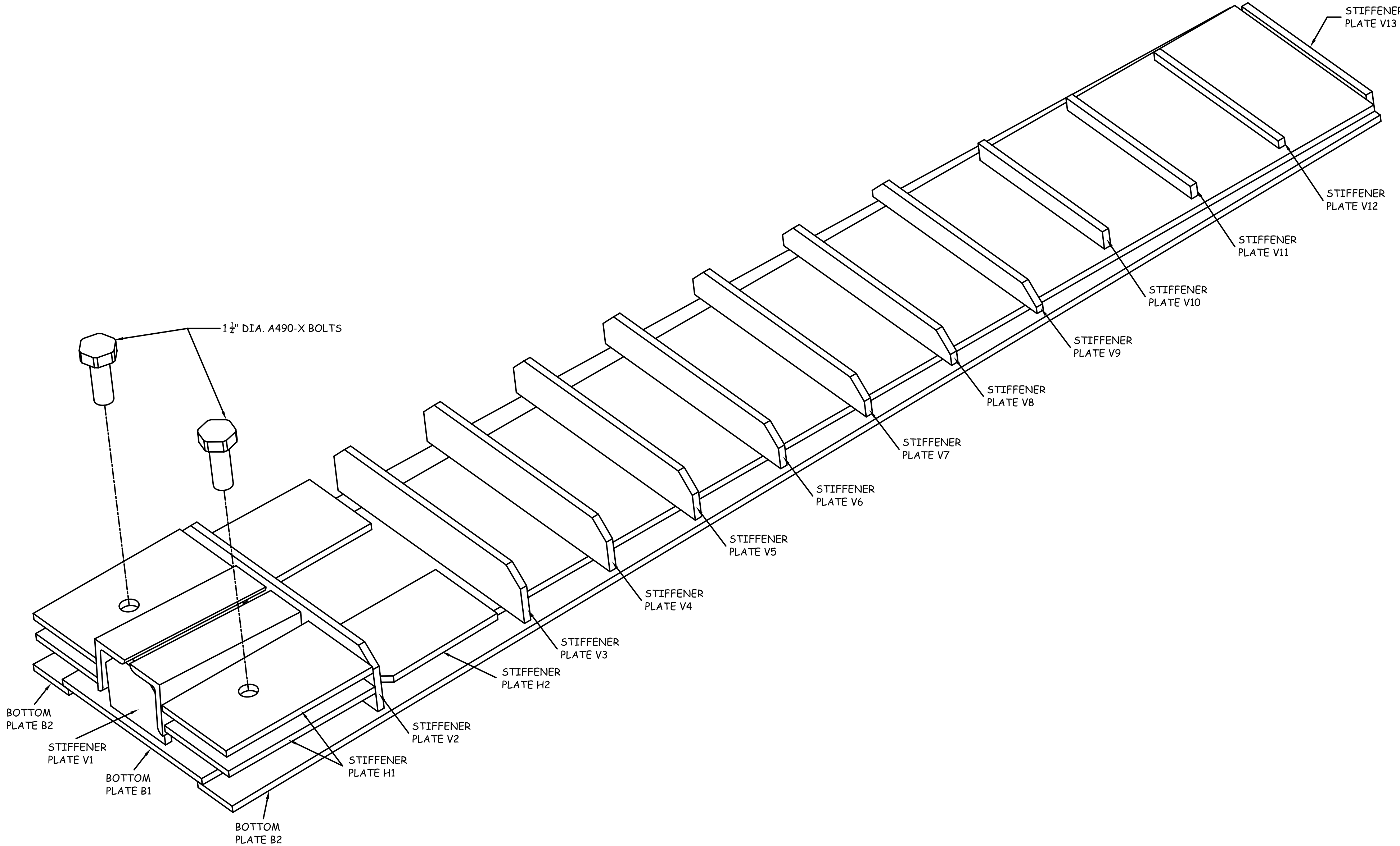
END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 14



A/15 ISOMETRIC VIEW OF STEEL SEGMENT

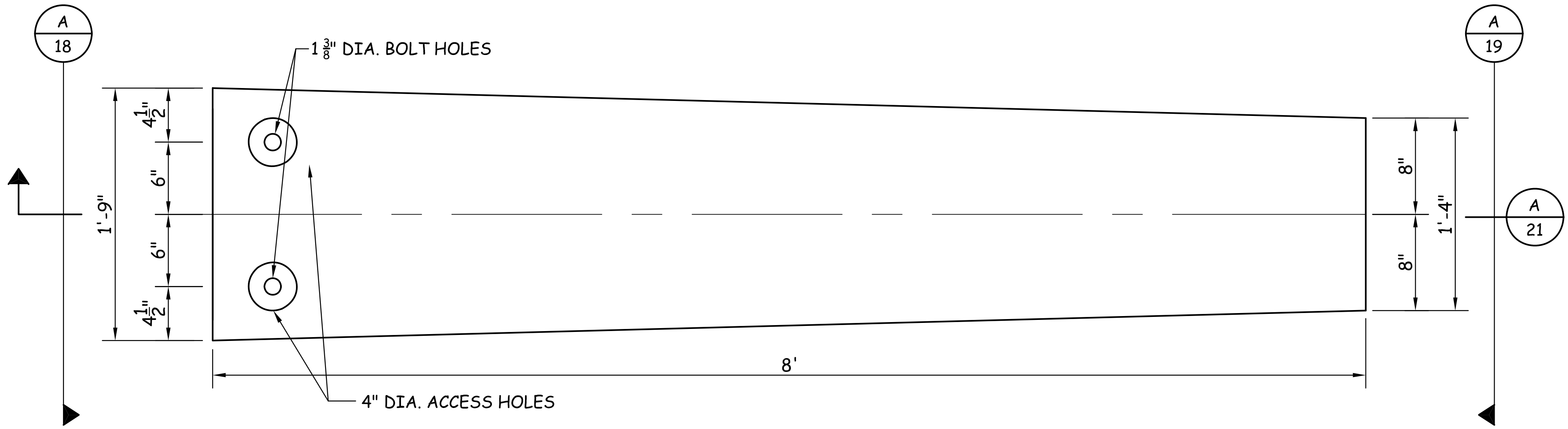
UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 15



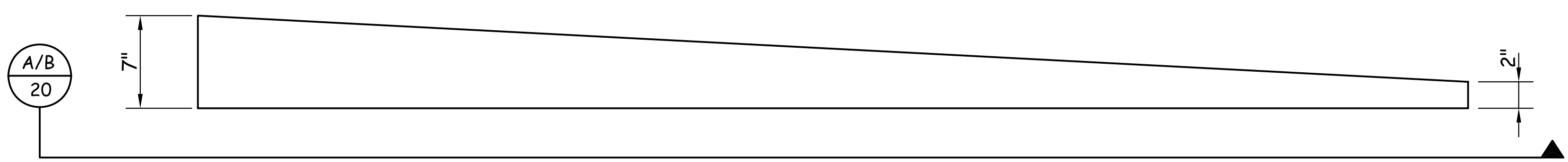
A/16 ISOMETRIC VIEW OF INTERNAL COMPONENTS OF STEEL SEGMENT

(OUTER PLATE OMITTED FOR CLARITY)

UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 16



A 17 PLAN VIEW OF STEEL SEGMENT

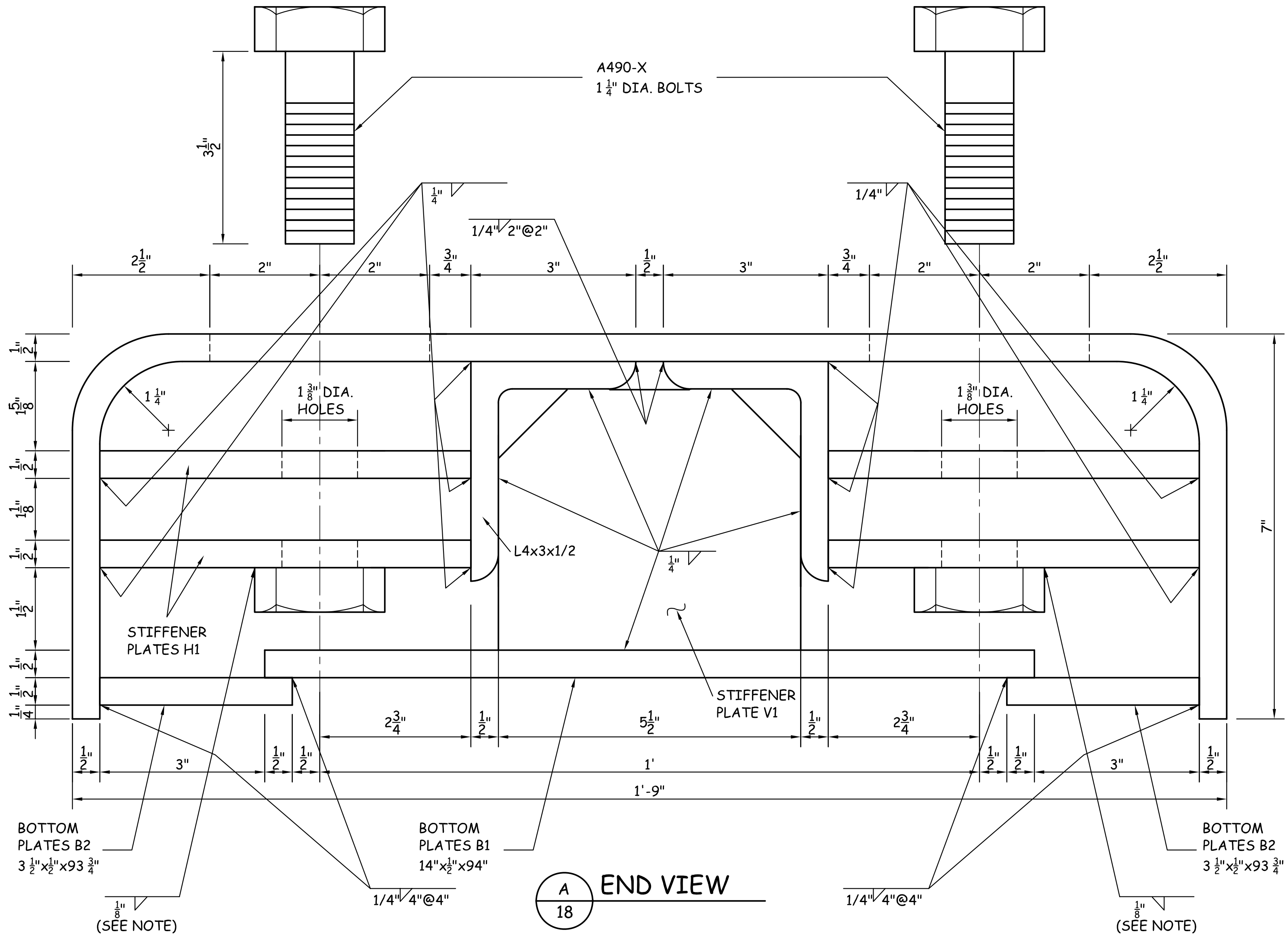


A 17 ELEVATION VIEW OF STEEL SEGMENT

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 17

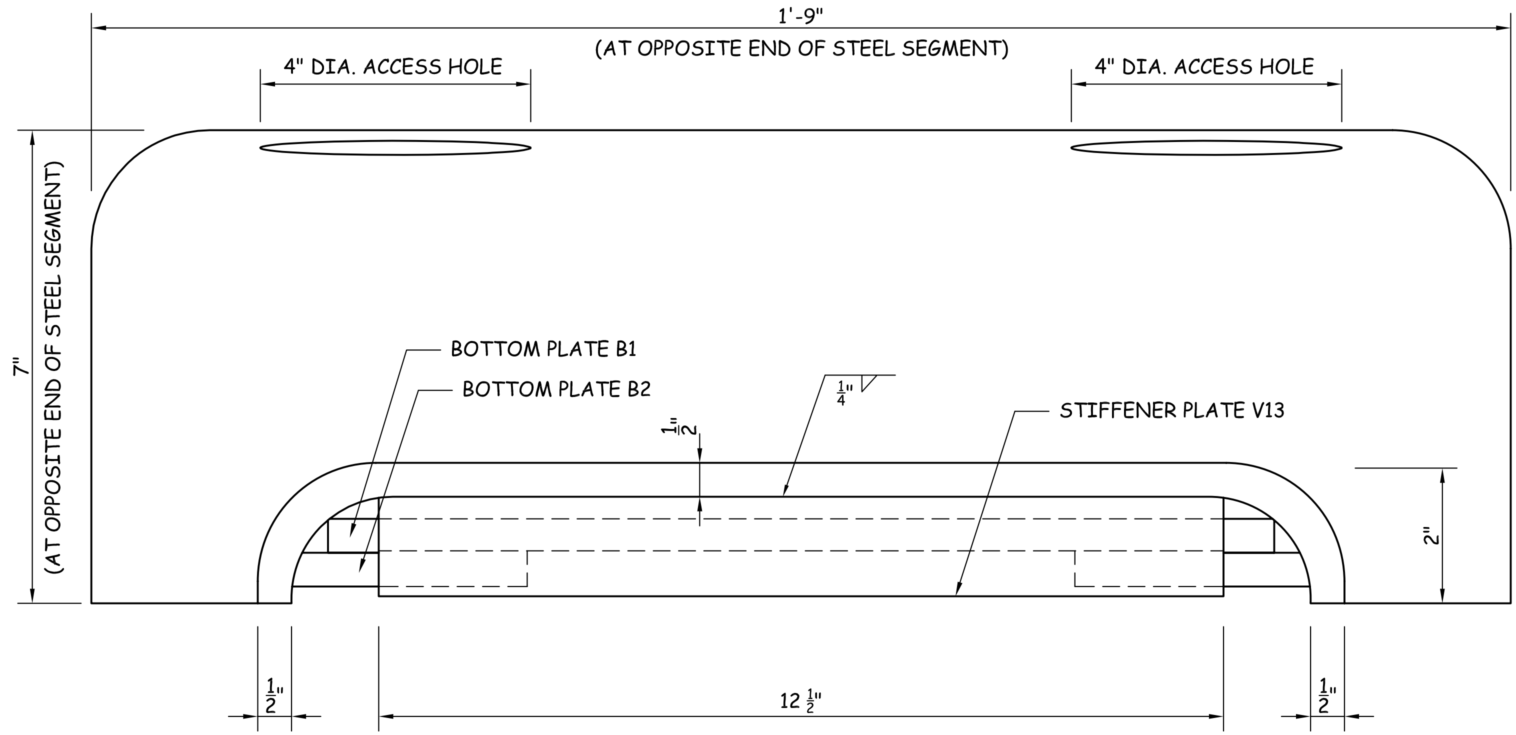


A
18
END VIEW

NOTE:

THREAD 1 1/4" LONG BOLT INTO NUT, PULL NUT FLUSH AGAINST STIFFENER PLATE H1, THEN WELD NUT (1/2 WAY AROUND) TO PLATE H1.

UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 18

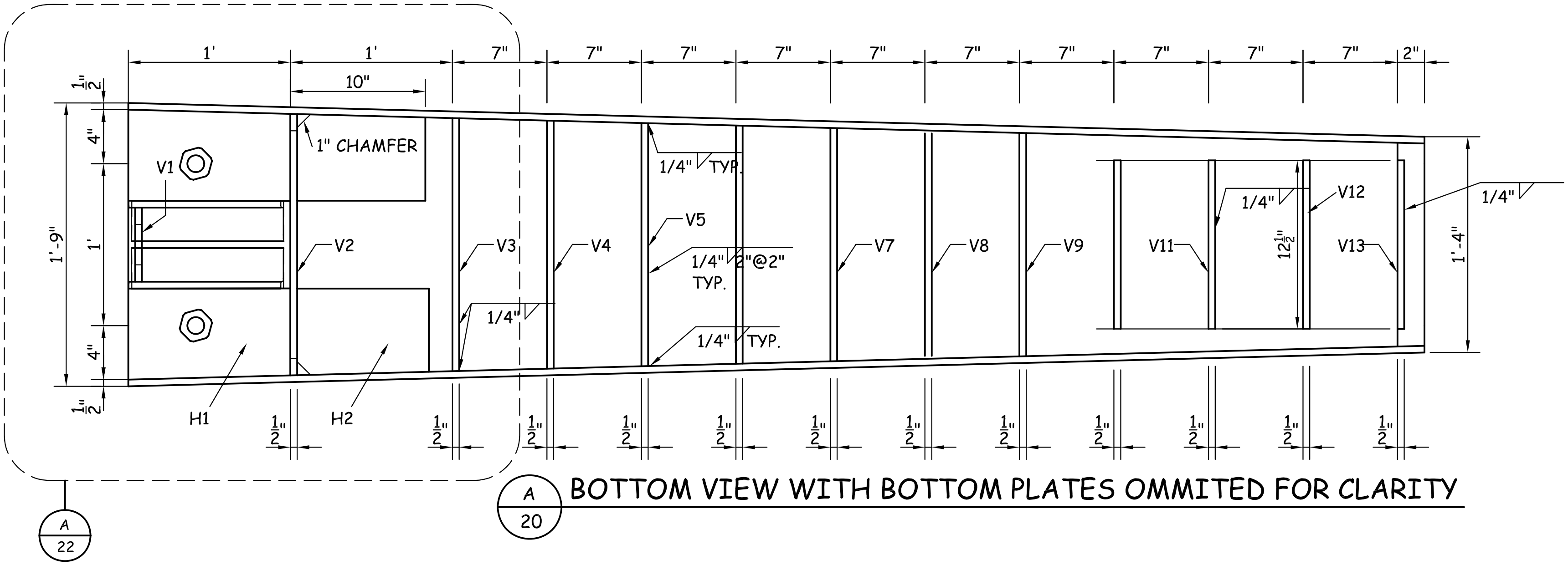


A/19 END VIEW

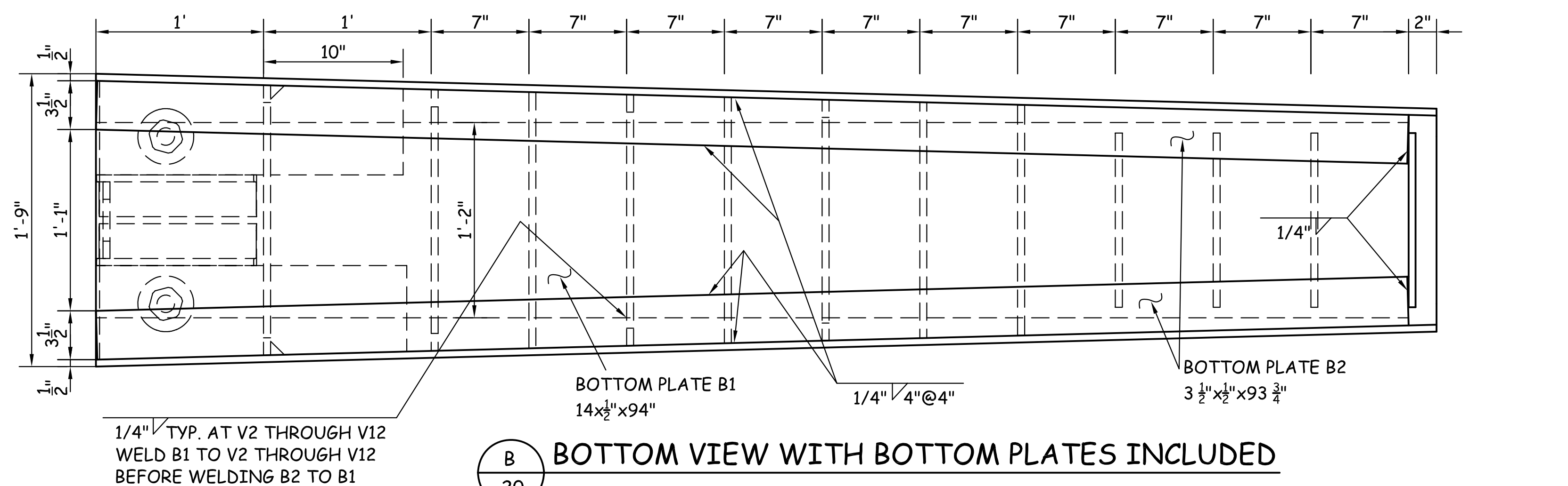
UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 19



A/20 BOTTOM VIEW WITH BOTTOM PLATES OMMITED FOR CLARITY

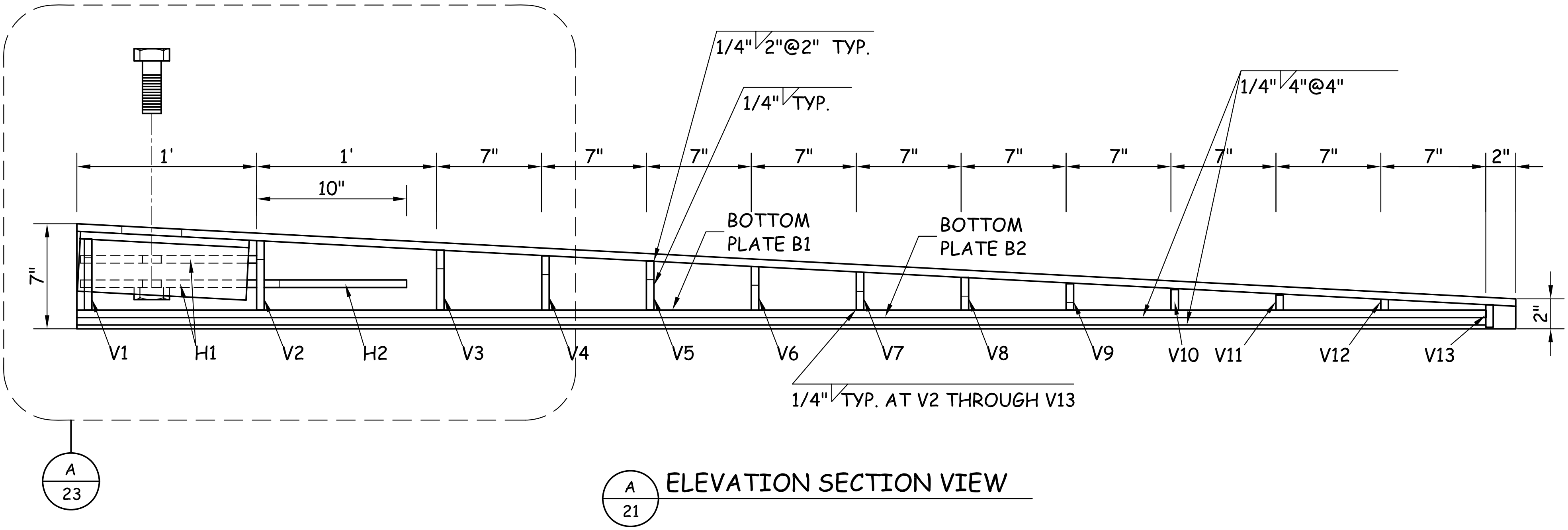


B/20 BOTTOM VIEW WITH BOTTOM PLATES INCLUDED

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 20

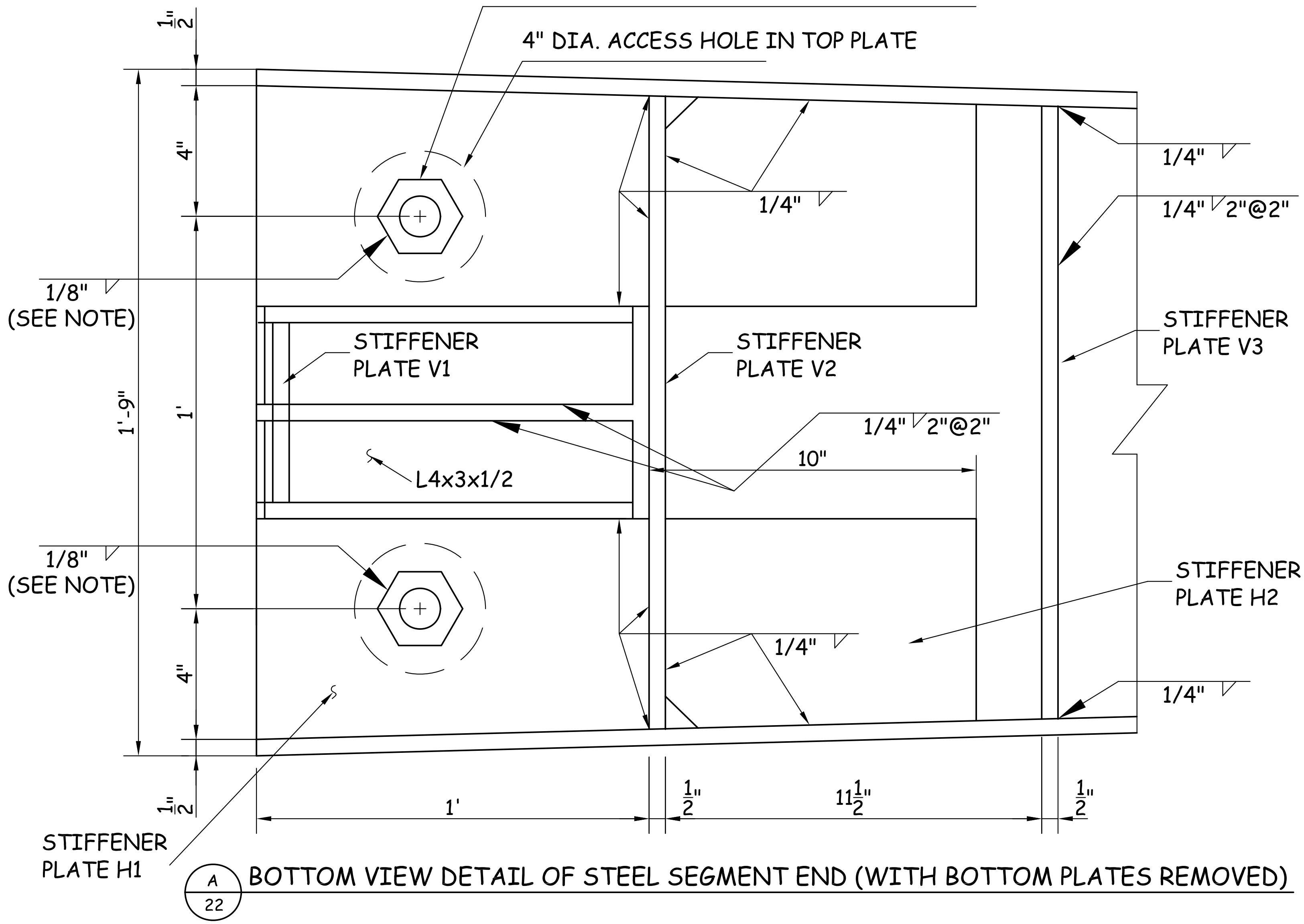


A 21 ELEVATION SECTION VIEW

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 21

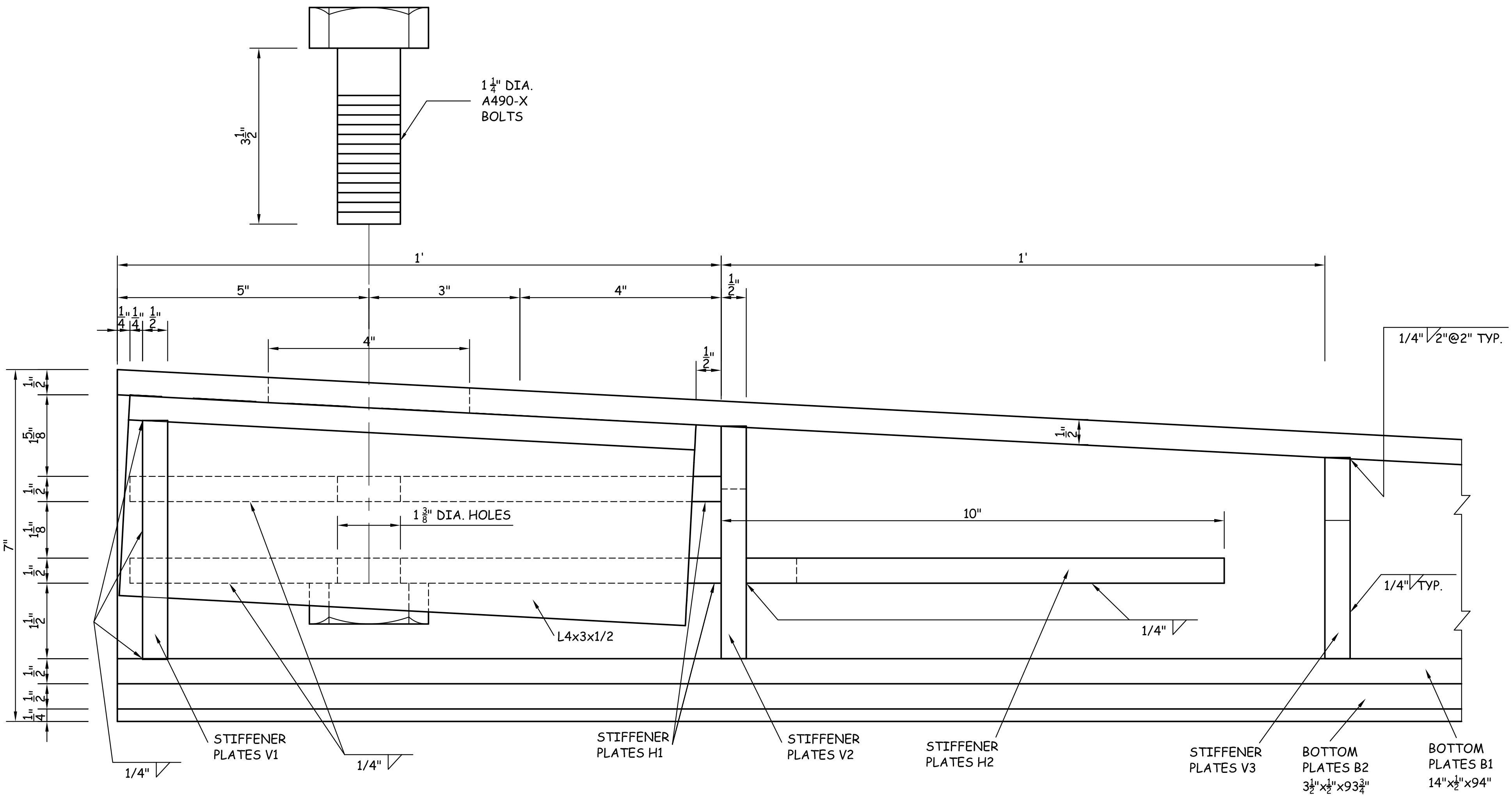


BOTTOM VIEW DETAIL OF STEEL SEGMENT END (WITH BOTTOM PLATES REMOVED)

NOTE:

THREAD $1\frac{1}{4}$" LONG BOLT INTO NUT, PULL NUT FLUSH AGAINST STIFFENER PLATE H1, THEN WELD NUT (1/2 WAY AROUND) TO PLATE H1.

UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 22



A/23 DETAIL SECTION OF STEEL SEGMENT END

UNIVERSITY OF FLORIDA

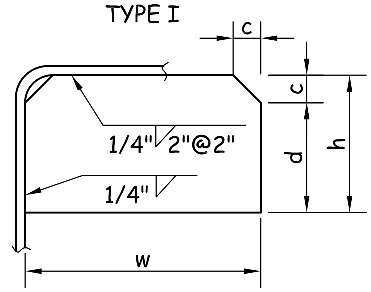
END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 23

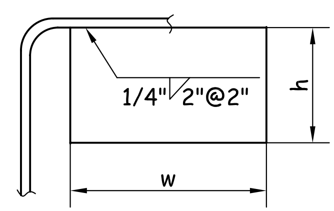
SCHEDULE FOR STIFFENER PLATES V1-V13

STIFFENER	TYPE	THICKNESS	w	h	c	d
V1	I	1/2"	5 1/2"	4 3/4"	1 1/4"	3 1/2"
V2	I	1/2"	19 3/8"	4 5/8"	1 1/4"	3 3/8"
V3	I	1/2"	18 3/4"	4"	1 1/4"	2 3/4"
V4	I	1/2"	18 3/8"	3 5/8"	1 1/4"	2 3/8"
V5	I	1/2"	18"	3 1/4"	1 1/4"	2"
V6	I	1/2"	17 5/8"	2 7/8"	1 1/4"	1 5/8"
V7	I	1/2"	17 1/4"	2 1/2"	1 1/4"	1 1/4"
V8	I	1/2"	16 7/8"	2 1/8"	1 1/4"	7/8"
V9	I	1/2"	16 1/2"	1 3/4"	1 1/4"	1/2"
V10	II	1/2"	12 1/2"	1 3/8"	—	—
V11	II	1/2"	12 1/2"	1"	—	—
V12	II	1/2"	12 1/2"	5/8"	—	—
V13	II	1/2"	12 1/2"	1 1/2"	—	—

TYPE I



TYPE II

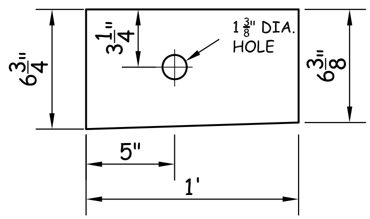


UNIVERSITY OF FLORIDA

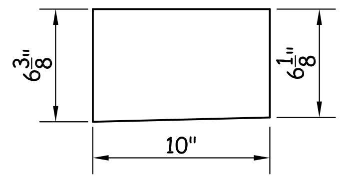
END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 24

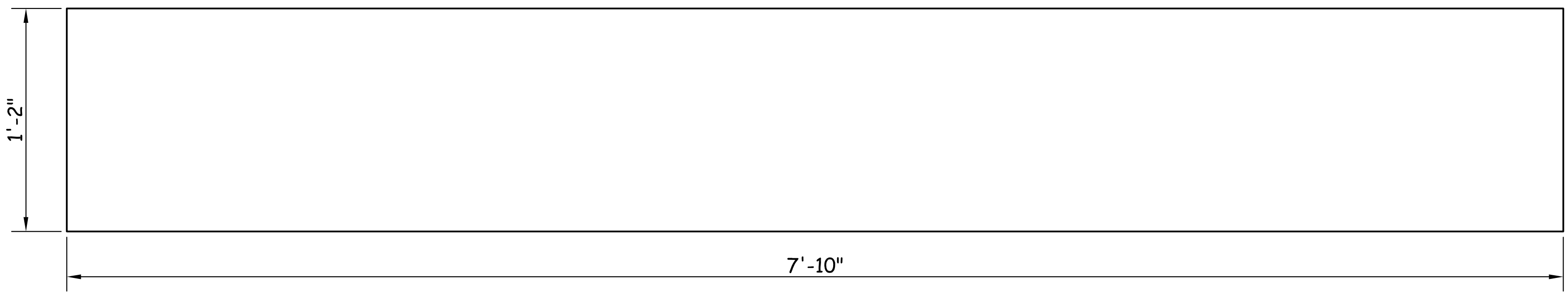
STIFFENER PLATE H1
QUANTITY: 4
$\frac{1}{2}$" THICK



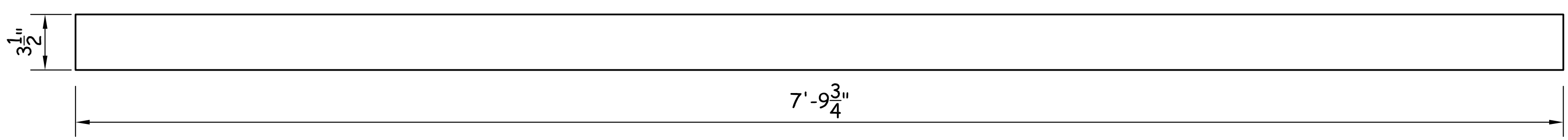
STIFFENER PLATE H2
QUANTITY: 2
$\frac{1}{2}$" THICK



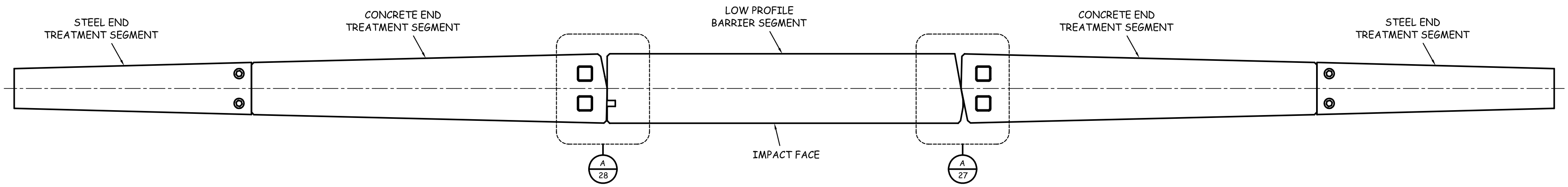
BOTTOM PLATE B1
QUANTITY: 1
$\frac{1}{2}$" THICK



BOTTOM PLATE B2
QUANTITY: 2
$\frac{1}{2}$" THICK

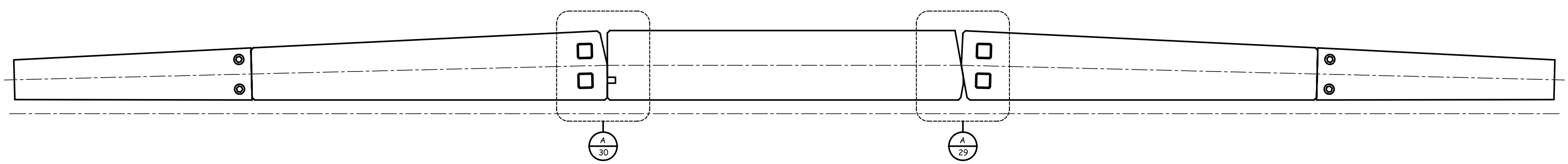


UNIVERSITY OF FLORIDA
END TREATMENT FOR LOW-PROFILE BARRIER WALL
SHEET NO. 25



A/26 PLAN VIEW OF END TREATMENT INSTALLED AT BOTH ENDS OF A SINGLE BARRIER SEGMENT

GEOMETRIC REFERENCE CONFIGURATION SHOWN: CENTERLINES OF BARRIER AND END-TREATMENT ARE ALIGNED



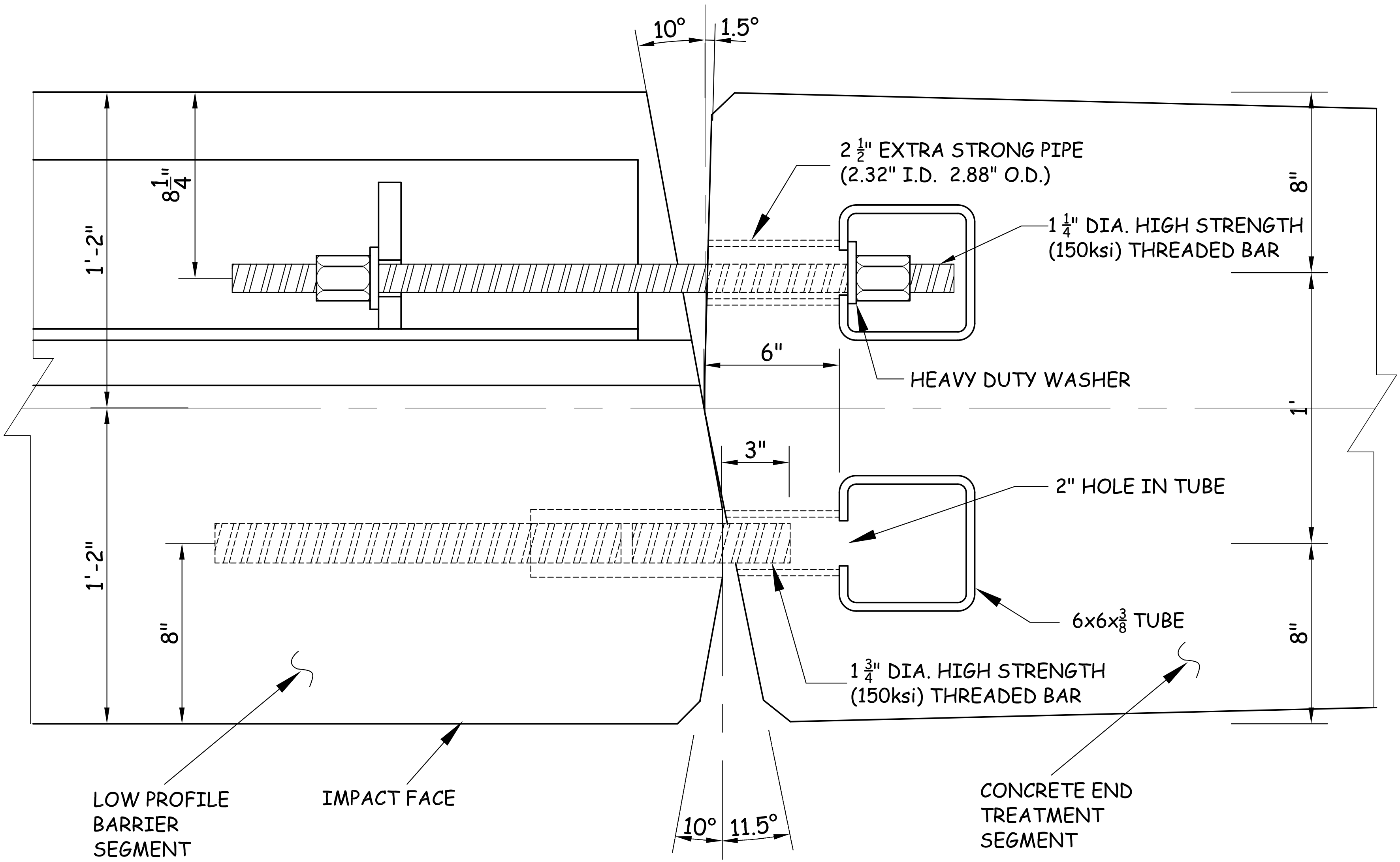
B/26 PLAN VIEW OF END TREATMENT INSTALLED AT BOTH ENDS OF A SINGLE BARRIER SEGMENT

FIELD INSTALLATION CONFIGURATION SHOWN: IMPACT FACES OF BARRIER AND END-TREATMENT ARE ALIGNED

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 26

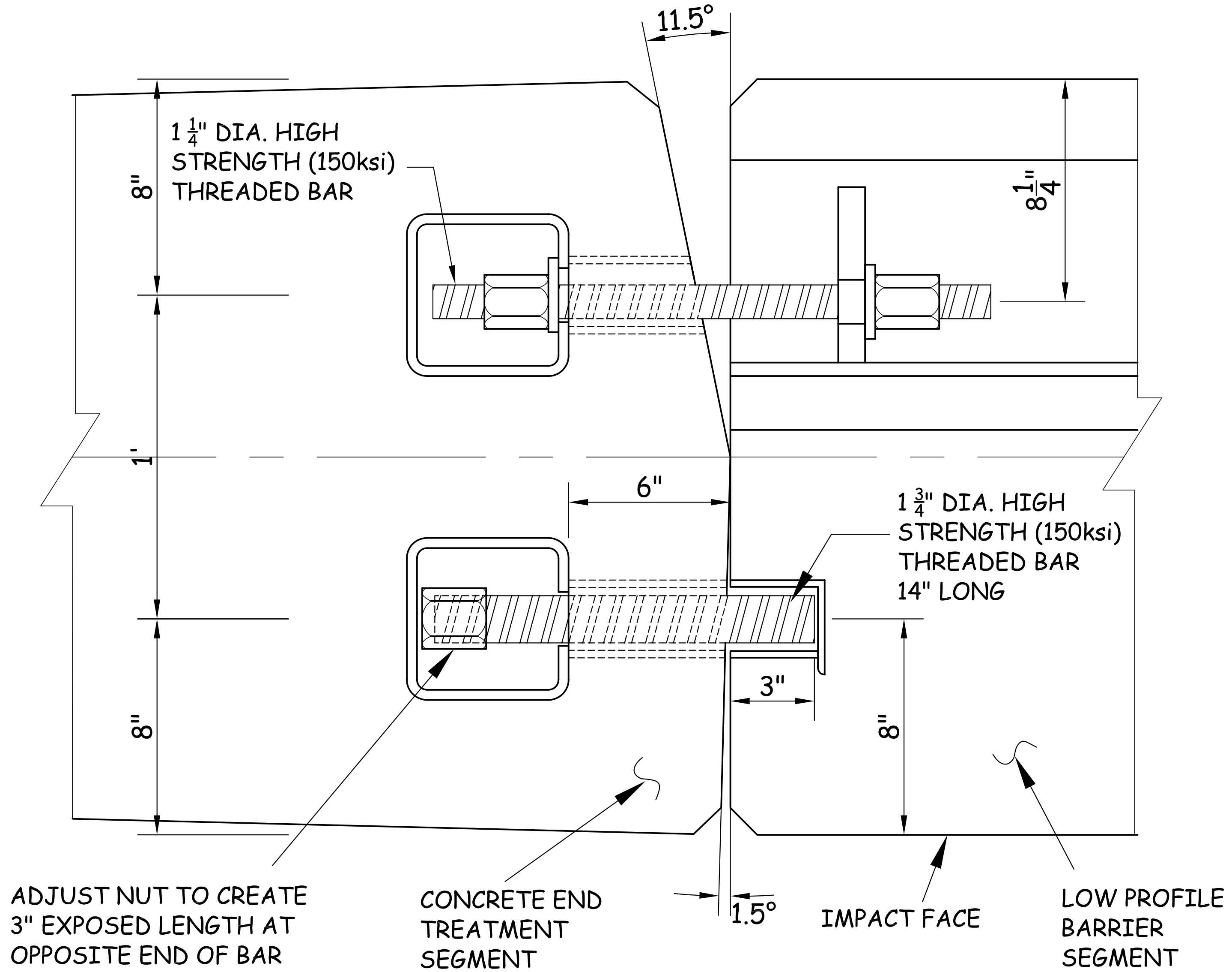


A/27 CONNECTION DETAIL

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 27

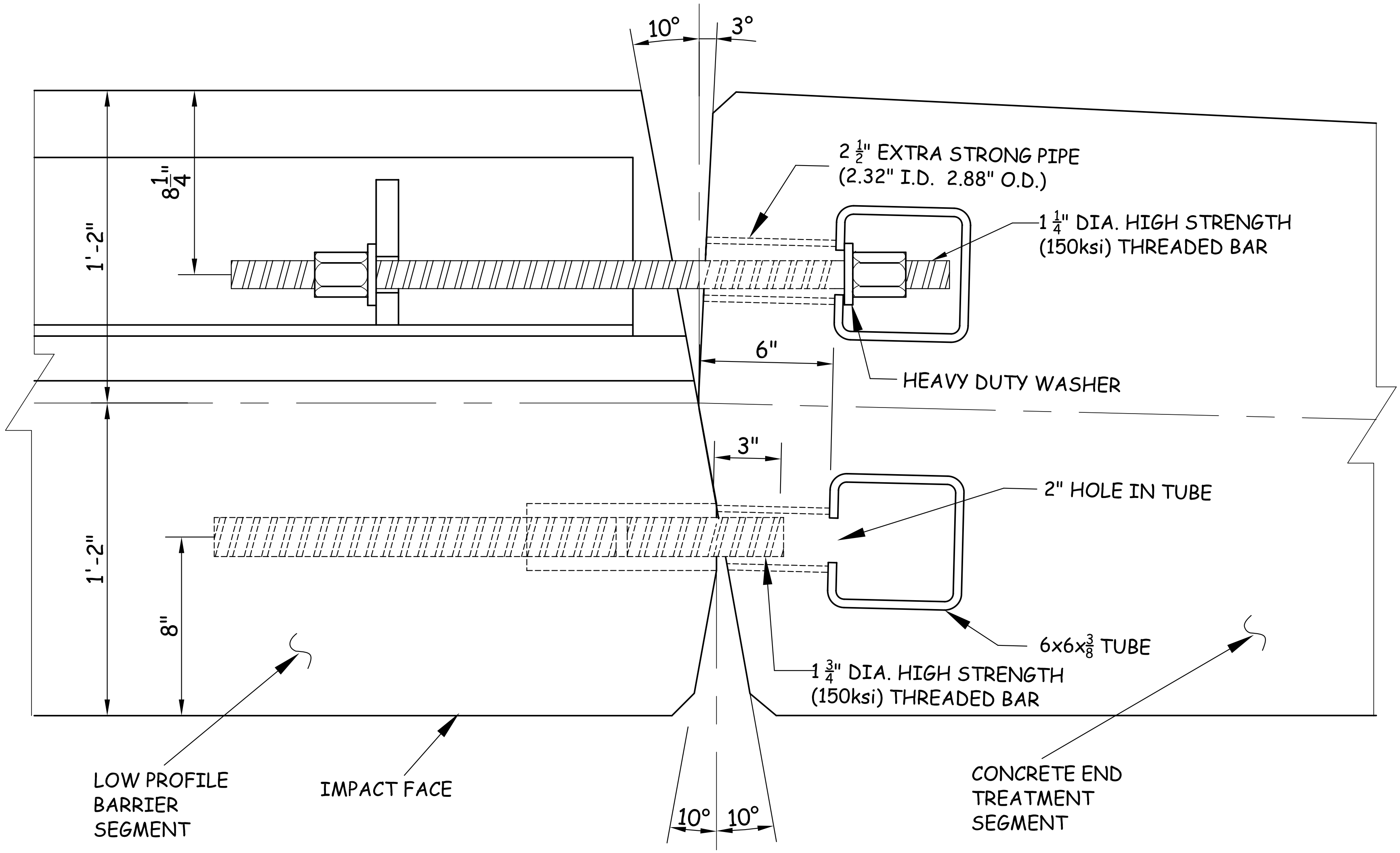


A/28 CONNECTION DETAIL

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 28

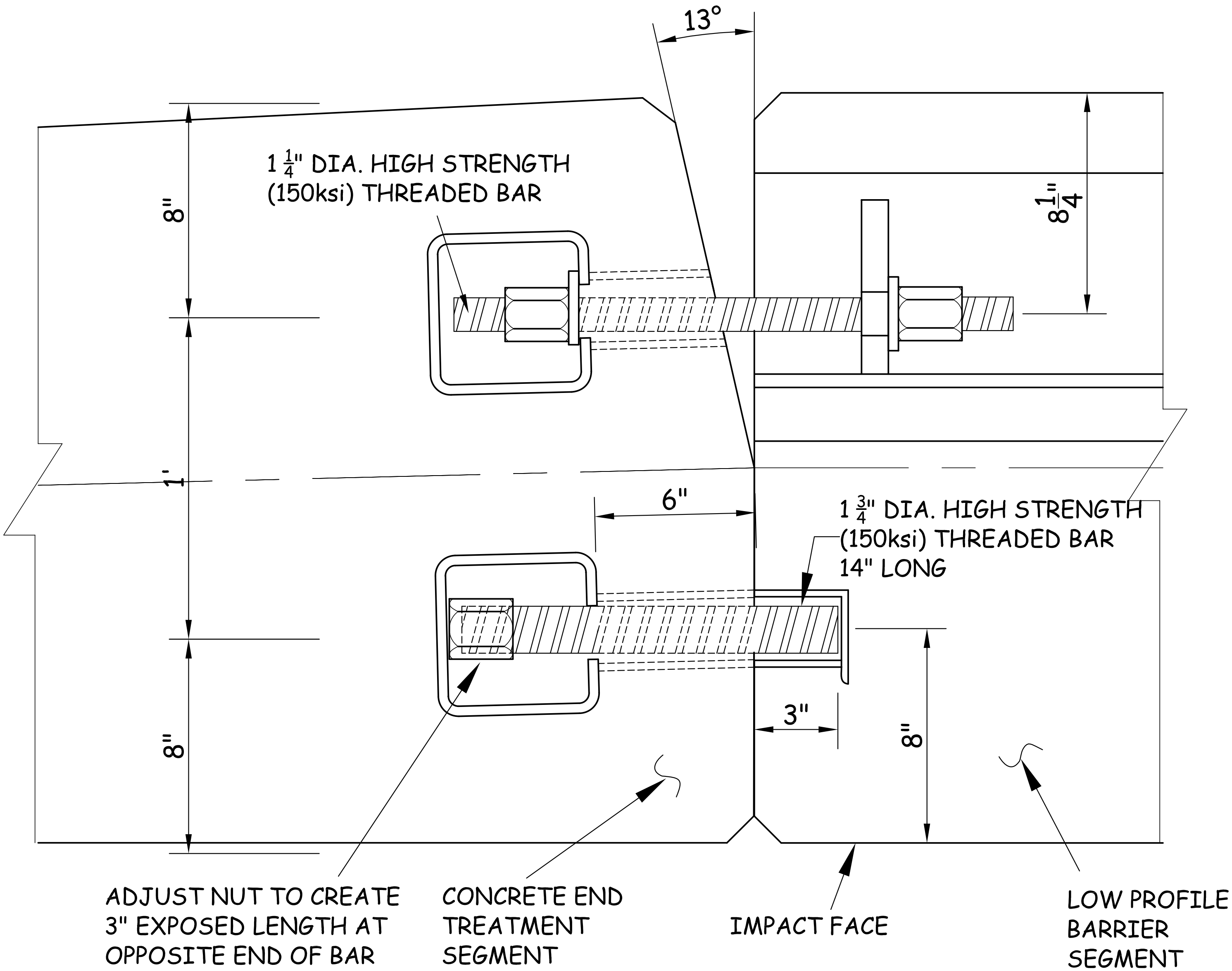


A/29 CONNECTION DETAIL

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 29



A/30 CONNECTION DETAIL

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

SHEET NO. 30

APPENDIX B

NCHRP REPORT 350 CRASH TEST RESULTS FOR THE UNIVERSITY OF FLORIDA PORTABLE CONCRETE CURB END-TREATMENT

NCHRP Report 350
Crash Test Results for the
University of Florida
Portable Concrete Curb End Treatment

Prepared for:

University of Florida
Gainsville, Florida 32611

Prepared by:

Manager
E-TECH Testing Services, Inc.
A Quixote Company
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Final Report #328
(Rev.1 - Supersedes Earlier Revisions)
Project No. 71-1776
August 2008

DISCLAIMER

This document was prepared by E-TECH Testing Services, Inc. under contract to the University of Florida. The contents of this report reflect the view of the author who is solely responsible for the findings and conclusions reported herein. The results presented in this report relate only to the University of Florida Portable Concrete Curb End Treatment tested.

SI CONVERSION FACTORS

To convert from	to	Multiply by
	ACCELERATION	
meter per second squared (m/s^2)	foot per second squared (ft/s^2)	3.280 840*E 00
	AREA	
square meter (m^2)	square foot (ft^2)	1.076 391*E 01
	ENERGY	
Joule (J)	foot-pound ($ft\text{-}lb_f$)	7.375 621*E-01
	FORCE	
Newton (N)	pound-force (lb_f)	2.248 089*E-01
	LENGTH	
meter (m)	foot (ft)	3.280 840*E 00
meter (m)	inch (in)	3.937 008*E 01
millimeter (mm)	inch (in)	3.937 008*E-02
	MASS	
kilogram (kg)	pound-mass (lb_m)	2.204 623*E 00
	PRESSURE OR STRESS	
Pascal (Pa)	pound per square inch (psi)	1.450 377*E-04
	VELOCITY	
kilometer per hour (km/h)	mile per hour (mph)	6.213 712*E-01
meter per second (m/s)	foot per second (ft/s)	3.280 840*E 00

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I. INTRODUCTION

A. Problem/Background

The State of Florida commissioned the University of Florida to design, develop, and evaluate a new type of longitudinal barrier called the portable concrete curb. In 2002 the University contracted with E-TECH to conduct full scale crash tests to evaluate the safety performance of the curb design. The curb was tested to Test Level 2 (70 km/ h) in compliance with the recommendations in the National Cooperative Highway Research Program Report 350 (NCHRP 350) for longitudinal barrier Tests 10 and 11.(1) The successful results of those tests were reported in November 2002.(2)

Subsequent to that time the State of Florida recommissioned the University to design, develop, and evaluate a crashworthy end treatment for the curb. The end treatment design was developed and evaluated with the aid of computer simulation. In 2008 the University once again contracted with E-TECH to conduct full scale crash tests to evaluate the safety performance of the end treatment design and thereby validate the computer simulation results. The end treatment was tested to Test Level 2 (70 km/ h) in compliance with the recommendations in the NCHRP 350 for gating end terminal Tests 30, 31, 32, 33, 34,35, and 39. The results of these tests are reported sequentially by NCHRP 350 test number in this report.

B. Objectives/Scope of Research

The objective of E-TECH Project 71-1776 was to conduct NCHRP 350 crash Tests 30, 31, 32, 33, 34,35, and 39 on the Florida Concrete Curb End Treatment, evaluate the results, and then report the findings. The results are presented sequentially by NCHRP 350 Test number in this report.

II. TECHNICAL DISCUSSION

A. Test Parameters

1. Test Facility

The reported tests were conducted at E-TECH Testing Services' Lincoln test facility that is located at 1420 Flight Line Drive, Lincoln, California. The test facility is situated on an abandoned airport runway and features a 5 ha full scale crash testing area. Available test pad foundations consist of NCHRP 350 "Strong" and "Weak" soil, compacted subbase, asphalt concrete, and reinforced Portland cement concrete. The University of Florida specified the Curb be placed freestanding and unanchored on a "worst case" aged asphalt chip seal foundation.

2. Test Article Design and Construction

The test articles, installation instructions, and desired test conditions for the crash test program were supplied by the University of Florida. The Florida Concrete Curb End Treatment is a gating terminal designed to allow controlled penetration of an errant vehicle when impacted in both head on and angled impacts on the nose of the device and side impacts upstream of the beginning of length of need (BLON). The length of need (LON) is that part of the terminal designed to contain and redirect an errant vehicle. The University specified the BLON as the connection point between the End Treatment and the first downstream concrete curb section.

A total of (15) curb sections were used downstream of the end treatment to construct a straight 54.9 m long test article installation. The construction details of the End Treatment are shown in Illustration D-1 *"Drawings of Florida Concrete Curb End Treatment"* of Appendix D. The material specifications for key components supplied by the manufacturer are shown in Illustration D-2 *"Material Specification"* of Appendix D and are kept on file.

The End Treatment is made up of two segments that bolt together to form a 6.1 m long sloped end terminal that tapers from 51 mm above ground level at the front to the 457 mm curb height at the rear. The width of the End Treatment tapers from 406 mm at the front to the 711 mm width of the downstream curb sections at the rear.

The front segment is manufactured from heavily reinforced 12.7 mm thick welded steel plate. The rear segment is manufactured from reinforced Portland cement concrete. The downstream end of the rear segment plugs into the steel rod that protrudes from the upstream end of the concrete curb and also has a gusseted steel pocket through which another 32 mm diameter high strength threaded rod is passed to complete the connection to the first curb section. The rod is fitted with a high strength nut that is tightened against the pocket to remove connection slack. During impact the rods effectively transfer the tension created between the End Treatment and the curb.

3. Test Vehicles

Commercially available production model crash test vehicles were used to evaluate the impact performance of the test article. As recommended in NCHRP 350, standard 820C (small car) and 2000P (3/4T Pickup Truck) vehicles were used. The static and dynamic properties of the test vehicles conformed to those recommended in NCHRP 350. Although the actual ages of the test vehicles were more than six years from the dates of the tests, their key properties were verified to conform to those specified in NCHRP 350 and thereby comply with recommendations concerning exceptions to vehicle age limitations.

The test vehicles were in good condition, free of major body damage and not missing structural parts. The vehicle bumpers and other structural elements were standard equipment and unmodified for the test. Vehicle tire sizes were in accordance with the manufacturer's suggested sizes. Before the tests, the battery and/or seats were removed or ballast was added, if necessary, to obtain the specified vehicle mass. The vehicles were towed up to the test speed and the prime mover was disengaged prior to impact. The steering mechanisms were disengaged from the guidance system prior to impact and were unconstrained thereafter.

The crash test vehicles were equipped with an emergency braking system that can be activated if the test needs to be aborted for safety reasons. On occasion, the braking system is applied after impact to prevent the vehicle from damaging testing equipment, or to prevent the vehicle from being damaged by secondary collisions with other fixed objects adjacent to the test area. Application of the brakes is delayed as long as safely feasible to establish the unbraked runout trajectory and velocity of the vehicle. Any application of the braking system is reported along with the approximate position of the vehicle at the time of brake application.

B. Test Conditions and Results

Florida Concrete Curb End Treatment
Test 71-1776-004
(NCHRP 350 Test 2-30)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-004 is summarized in Figure 1. Details of the test article installation are given in Section II.A.2. and Appendix D of this report.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a small 820C passenger vehicle under a head on center, one quarter vehicle width offset, impact on the test article. The test was run on May 16, 2008 using a white 1988 Ford Festiva. The pre-test photographs are shown in Figure 2. The curb mass of the vehicle was 818 kg and the final test inertial mass was 832 kg. A 75 kg anthropomorphic dummy was restrained in the passenger seat. The impact severity was 161.7 kJ which was within the NCHRP 350 recommended tolerance of 154.9 (-17.2/ +18.2) kJ.

The vehicle was offset 0.4 m toward the back side of the installation when it made contact with the End Treatment. The underside of the vehicle engaged the sloped surface and the vehicle pitched up onto the down stream curb and lost contact with the ground then came back down onto the downstream curb sections. The vehicle skidded along the top of five downstream curb sections then rolled off the back side of the curb, came back into contact with the ground, and lost contact with the test article. The vehicle exited at an angle of 23 deg relative to installation centerline and a speed of 60.1 km/h when it lost contact with the test article. The vehicle passed behind the test article and did not experience excessive roll, pitch, or yaw. The emergency braking system was applied approximately 25 m after loss of contact and the vehicle skidded to a stop 47.1 m downstream and 13.2 to the back side of the point of impact. There was no lateral dynamic or permanent deflection of the test article.

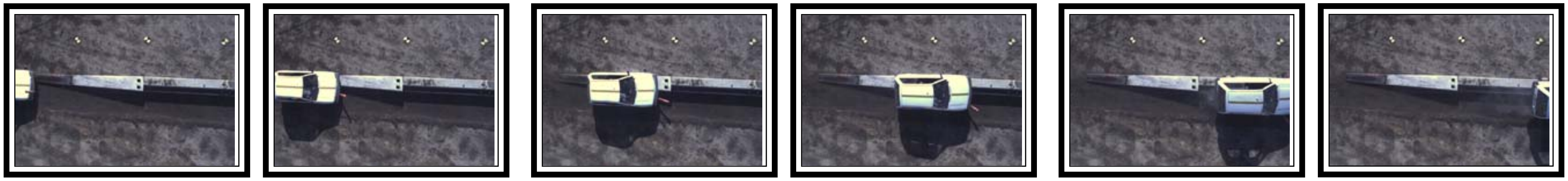
The theoretical occupant impact velocity values in the longitudinal and lateral directions were 1.0 and -0.3 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -3.9 and 3.0 g's respectively. The Theoretical Head Impact Velocity (THIV) was 5.5 km/h and the Post-Impact Head Deceleration (PHD) was 4.6 g's. The Acceleration Severity Index (ASI) was 0.3. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 24.8, 15.3 and 42.7 deg respectively.

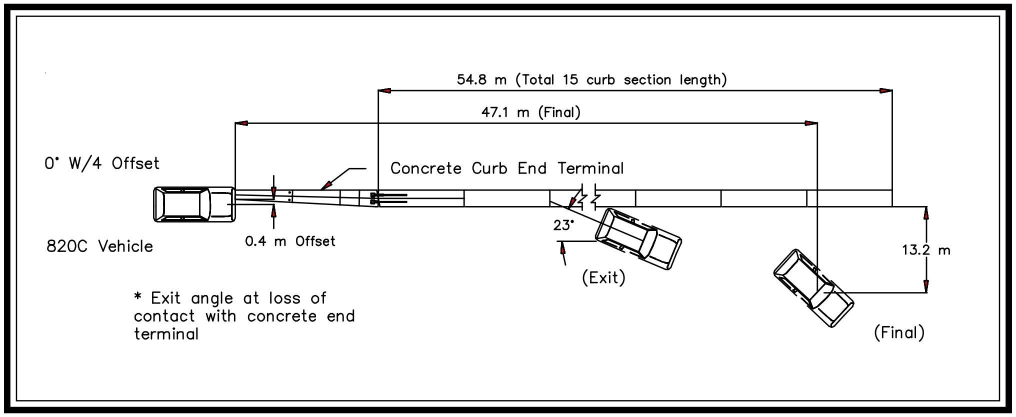
Test Article Damage/Debris Pattern

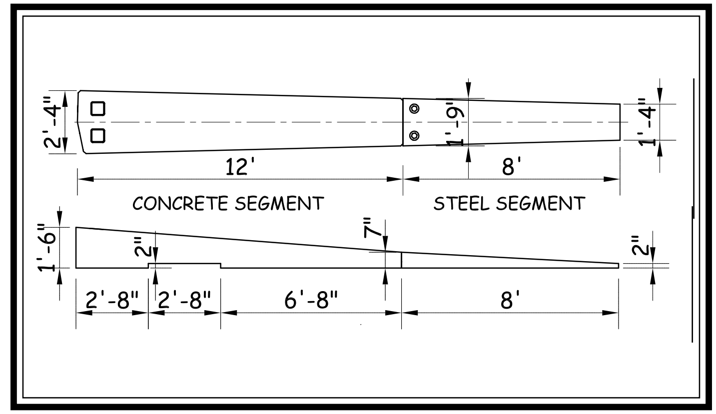
The test article damage is shown in the post-test photographs of Figure 3. There was negligible dynamic and permanent deflection of the test article. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. [3] There was no debris expelled by the test article.

Vehicle Damage

The vehicle damage is shown in Figure 4. There was essentially no damage to the test vehicle other than scrapes along the undercarriage and a flat tire consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC).[4][5] There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 5.



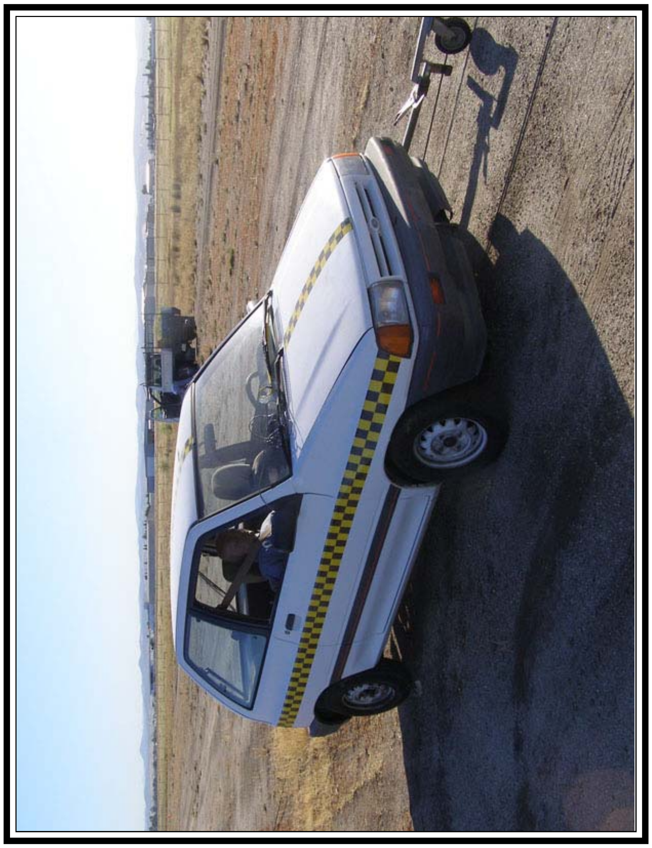


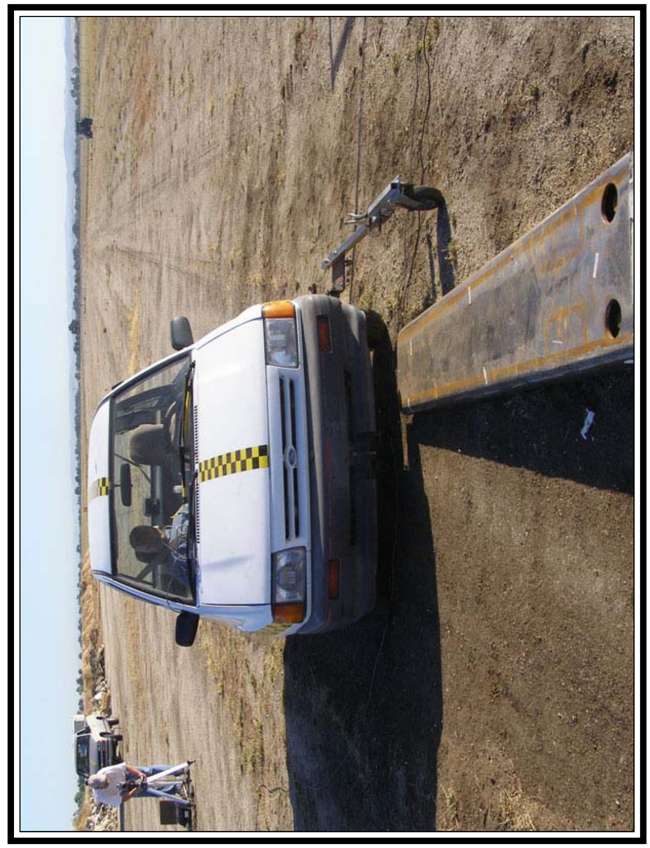


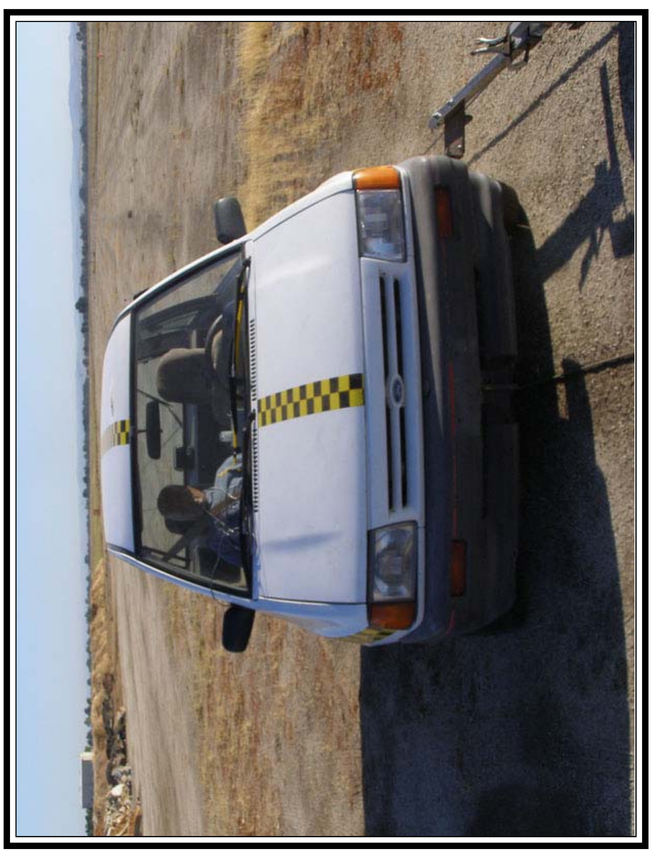
General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 2-30
Test No.	71-1776-004
Date	5/16/08
Test Article	
Type	University of Florida Concrete Curb End Treatment 6.1 m length
Installation Length	60.9 overall with (15) curbs
Material and key elements	Terminal: (1) 2.4 m long Steel Segment and (1) 3.7 m Concrete Segment, Barrier: (15) 3.7 m Curb Segments
Foundation Type and Condition	Aged chip seal asphalt, dry
Test Vehicle	
Type	Production Model
Designation	820C
Model	1988 Ford Festiva
Mass (kg)	
Curb	818
Test inertial	832
Dummy	75
Gross Static	907
Impact Conditions	
Speed (km/h)	71.0
Angle (deg)	0
Impact Severity (kJ)	161.7

Exit conditions	
Speed (km/h)	60.1
Angle (deg - veh. c.g.)	23
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	1.0
y-direction	-0.3
Ridedown Acceleration (g's)	
x-direction	-3.9
y-direction	3.0
European Committee for Normalization (CEN) Values	
THIV (km/h)	5.5
PHD (g's)	4.6
ASI	0.3
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	24.8
Maximum Pitch Angle	15.3
Maximum Yaw Angle	42.7
Test Article Deflections (m)	
Dynamic	N/A
Permanent	N/A
Vehicle Damage (Primary Impact)	
Exterior	
VDS	N/A
CDC	N/A
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 1. Summary of Results - Florida Curb End Treatment Test 71-1776-004







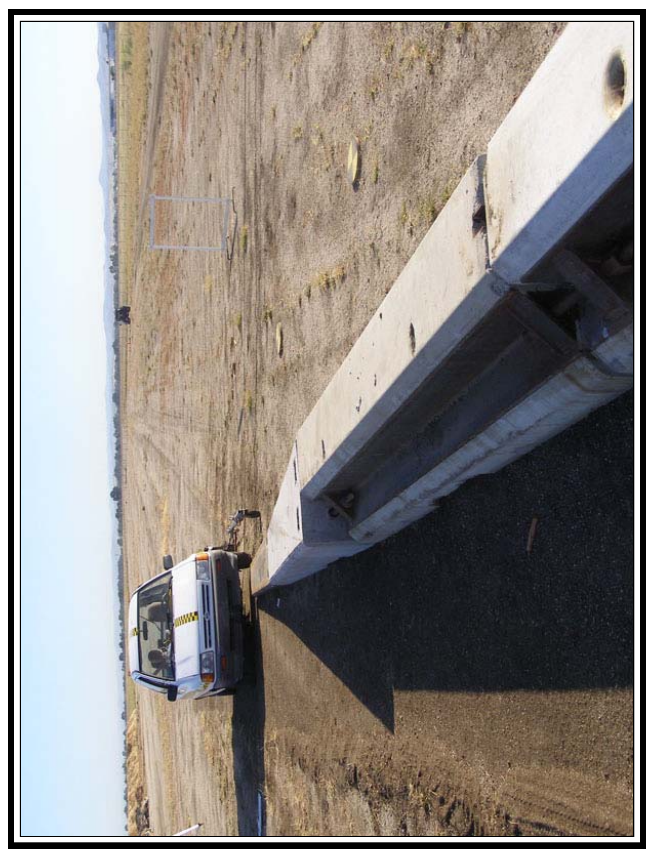


Figure 2. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-004

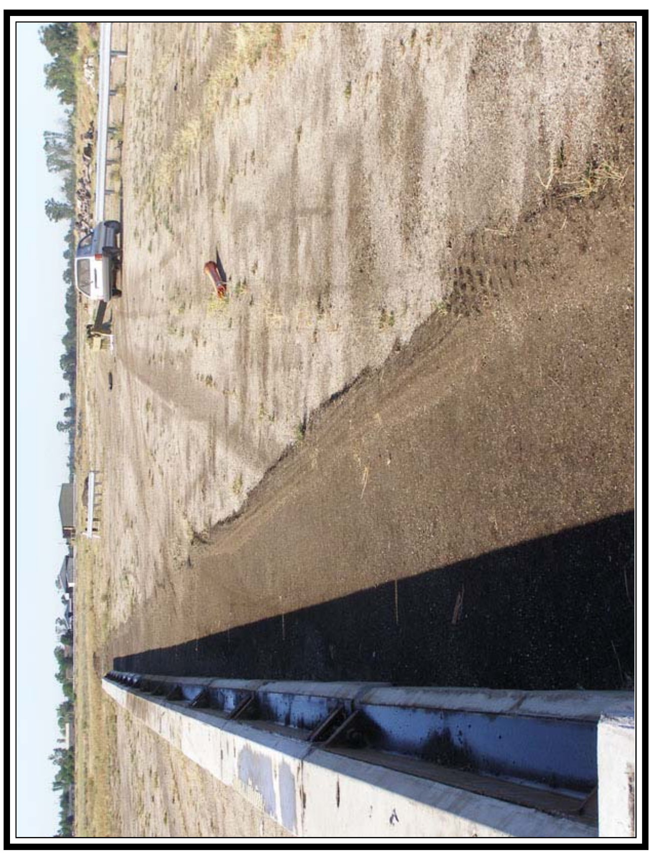
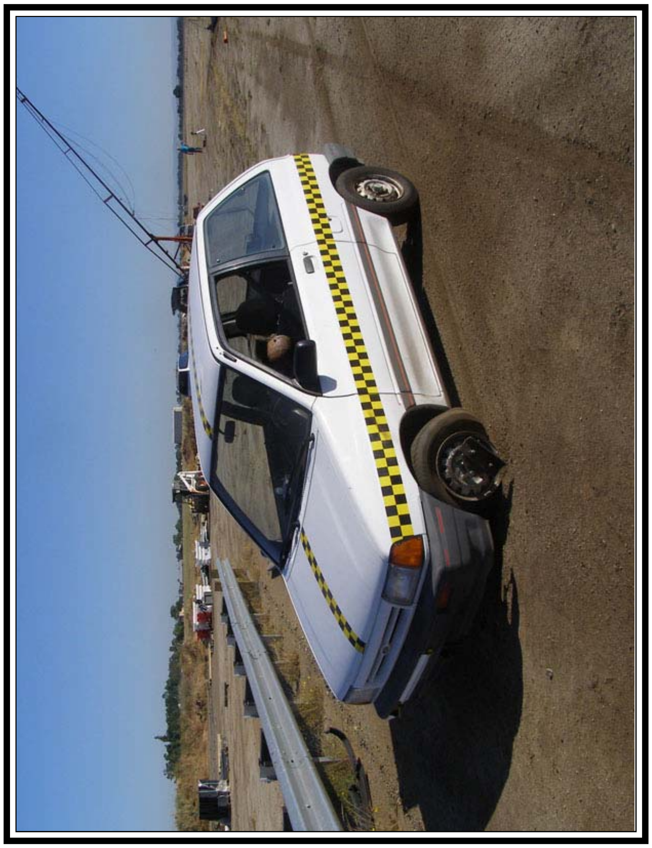


Figure 3. Test Article Damage - Florida Curb End Treatment Test 71-1776-004



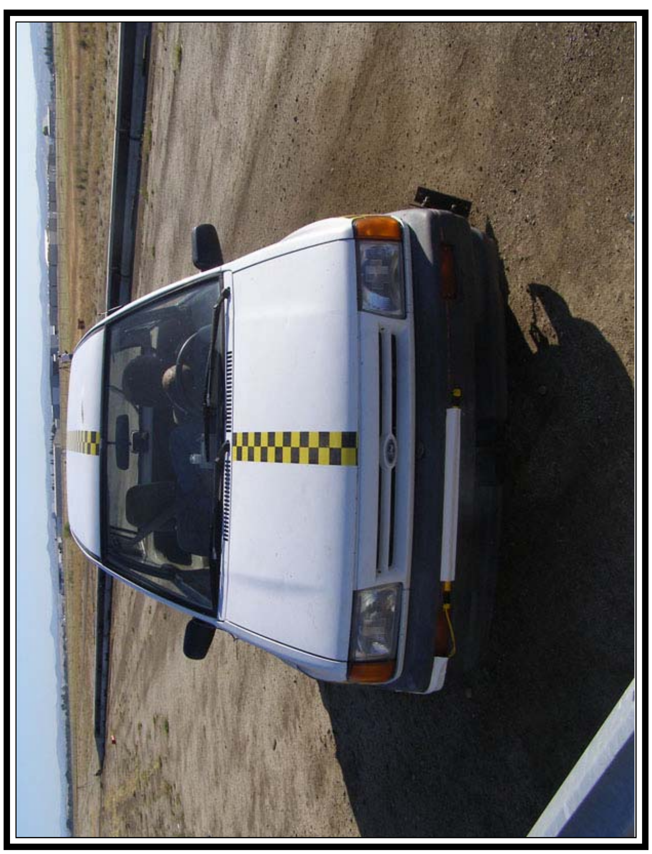


Figure 4. Vehicle Damage - Florida Curb End Treatment Test 71-1776-004

VEHICLE GEOMETRY 820C

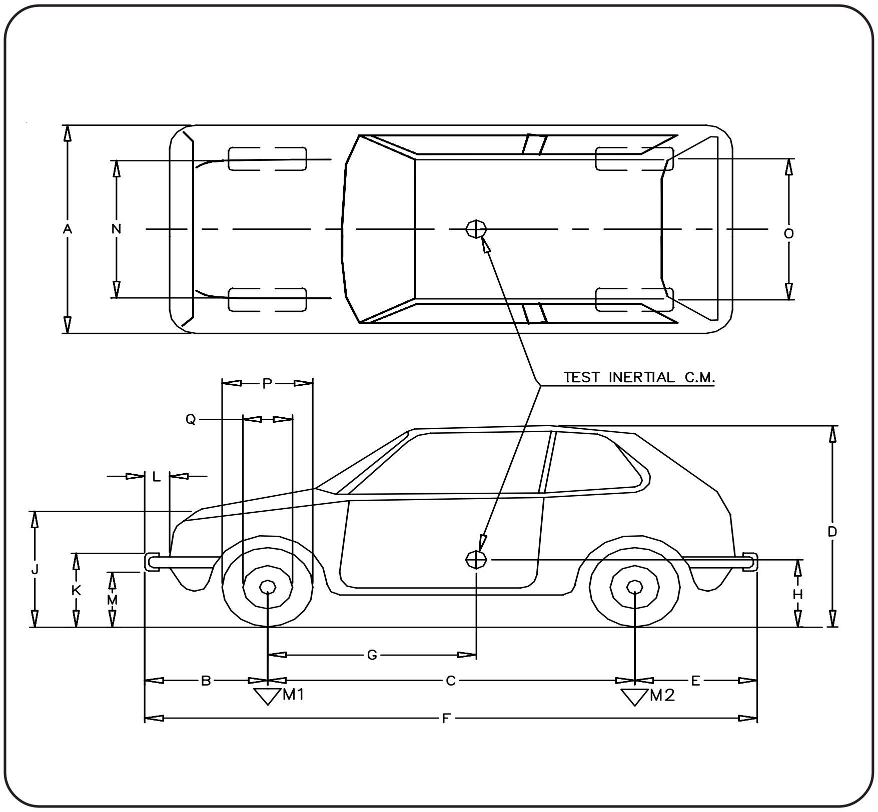
Test No: 71-1776-004

Date: 05/16/08

		Test Inertial Mass Distribution (kg):	
Make:	Ford	**LF**	281.5
Model:	Festiva	**RF**	263.0
Year:	1988	**LR**	142.0
Odometer:	231342	**RR**	145.5

Describe any damage to vehicle prior to test:
small dent in rear right panel

VIN No.
KNJBT07K0J6153027



Engine Type: 4 Cylinder

Engine CID: 1.3 Liter

Transmission Type: Manual

Optional Equipment: a.c.

Dummy Data:

Type: Anthropomorphic
Mass: 75 kg
Seat: Passenger

Pretest Geometry - cm.

A	160.0	**D**	142.0	**G**	77.7	**K**	53.0	**N**	140.0	**Q**	30.7
B	58.0	**E**	68.0	**H**	45.0	**L**	10.0	**O**	138.0		
C	225.0	**F**	351.0	**J**	70.0	**M**	40.0	**P**	54.0		

Mass - kg	**Curb**	**Test Inertial**	**Gross Static**
M_1	533	544	593
M_2	285	288	314
M_T	818	832	907

Figure 5. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-004

Florida Concrete Curb End Treatment
Test 71-1776-005
(NCHRP 350 Test 2-31)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-005 is summarized in Figure 6. Details of the test article installation are given in Section II.A.2. and Appendix D of this report. The test article exhibited only minor cosmetic damage from earlier test(s) and was essentially functioning as new.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a large 2000P passenger vehicle under a head on centered impact on the test article. The test was run on May 20, 2008 using a gold 1988 Chevrolet C2500 pickup. The pre-test photographs are shown in Figure 7. The curb mass of the vehicle was 1837 kg and the final test inertial mass was 1999 kg. The actual impact conditions were 72.0 km/h and 0 deg. The impact severity was 400.2 kJ which was within the NCHRP 350 recommended tolerance of 377.9 (-41.9/ +44.4) kJ.

The underside of the vehicle made contact with the End Treatment then the vehicle pitched up onto the down stream curb and lost contact with the ground. The vehicle skimmed along the top of the entire downstream curb sections, dropped off at the far end, and skidded to a stop. The vehicle exited at an angle of 10 deg relative to installation centerline and a speed of 43.2 km/h when it lost contact with the test article. The vehicle did not experience excessive roll, pitch, or yaw. The emergency braking system was applied approximately 10 m after loss of contact and the vehicle skidded to a stop 102 m downstream and 2.2 to the front side of the point of impact. There was no lateral dynamic or permanent deflection of the test article.

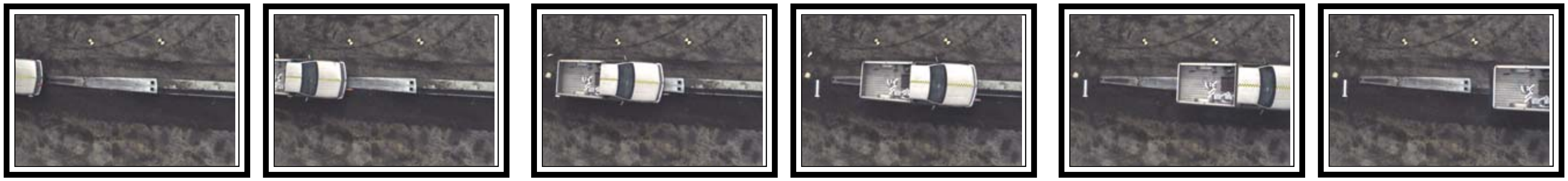
The theoretical occupant impact velocity values in the longitudinal and lateral directions were 1.5 and -0.3 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -2.2 and -1.3 g's respectively. The Theoretical Head Impact Velocity (THIV) was 5.7 km/h and the Post-Impact Head Deceleration (PHD) was 2.2 g's. The Acceleration Severity Index (ASI) was 0.3. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 15.3, 29.1, and -10.6 deg respectively.

Test Article Damage/Debris Pattern

The test article damage is shown in the post-test photographs of Figure 8. There was negligible dynamic and permanent deflection of the test article. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. There was no debris expelled by the test article.

Vehicle Damage

The vehicle damage is shown in Figure 9. There was essentially no damage to the test vehicle other than scrapes along the undercarriage consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC). There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 10.



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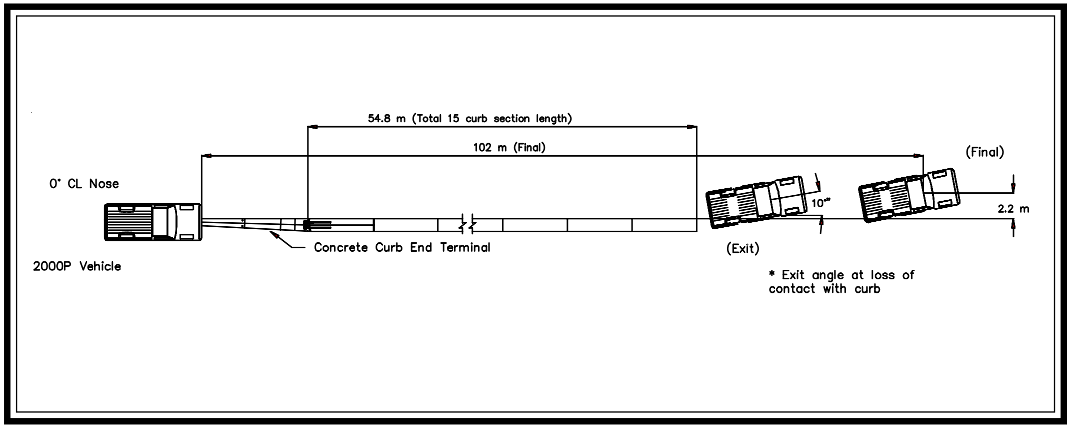

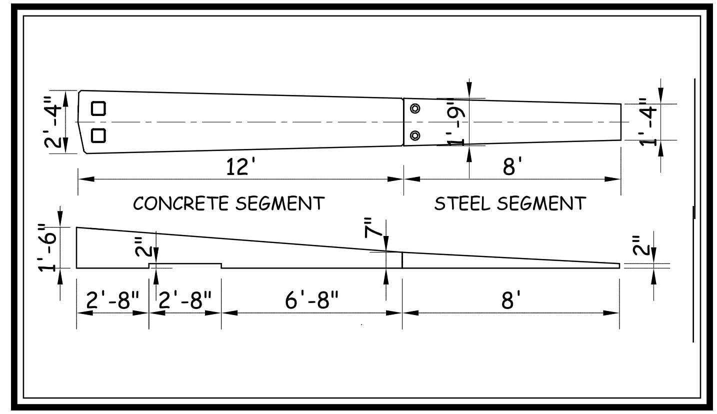

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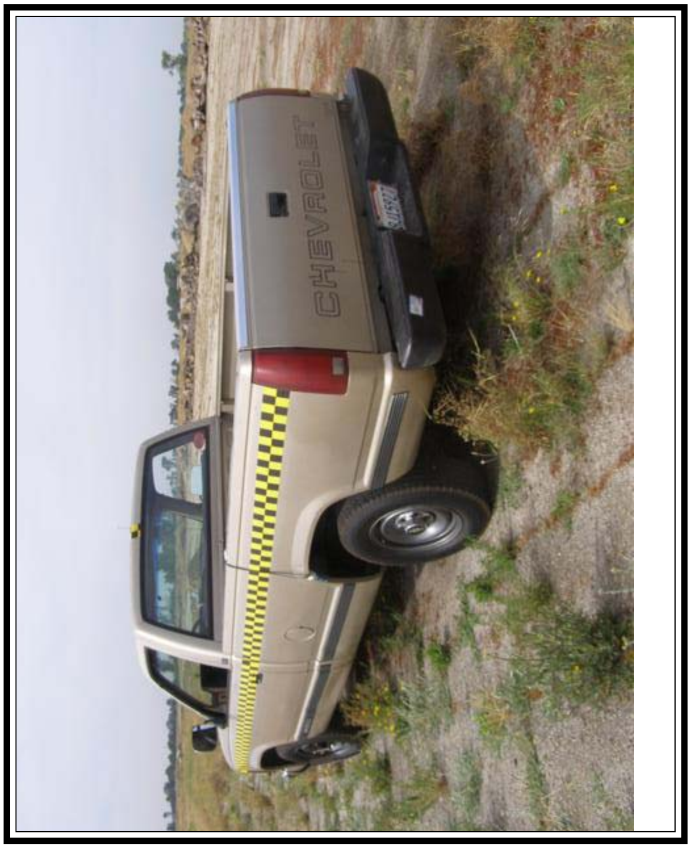
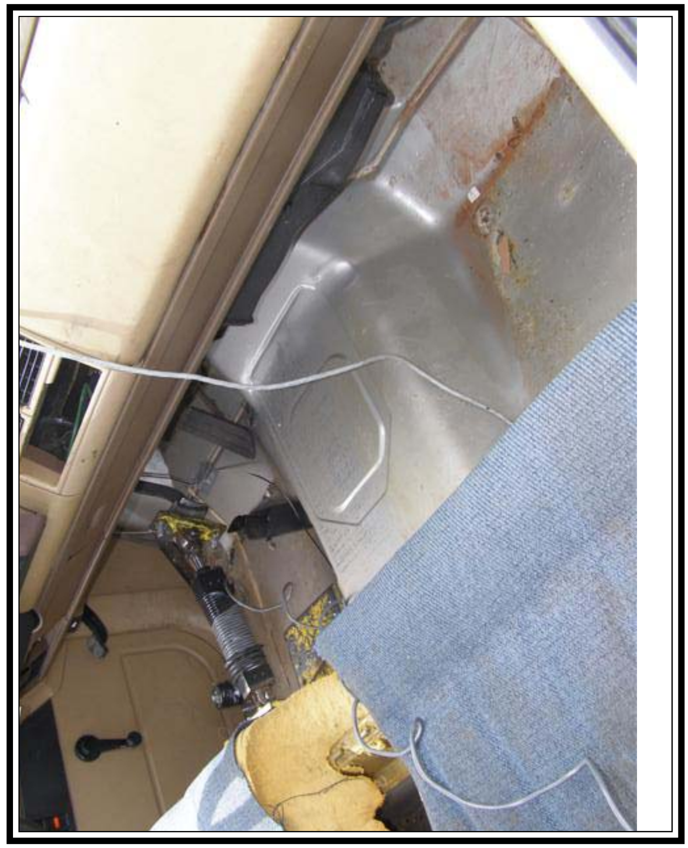
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 2-31
Test No.	71-1776-005
Date	5/20/08
Test Article	
Type	University of Florida Concrete Curb End Treatment 6.1 m length
Installation Length	60.9 overall with (15) curbs
Material and key elements	Terminal: (1) 2.4 m long Steel Segment and (1) 3.7 m Concrete Segment, Barrier: (15) 3.7 m Curb Segments
Foundation Type and Condition	Aged chip seal asphalt, dry
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1988 Chevrolet Pickup
Mass (kg)	
Curb	1837
Test inertial	1999
Dummy	N/A
Gross Static	1999
Impact Conditions	
Speed (km/h)	72.0
Angle (deg)	0
Impact Severity (kJ)	400.2
Exit conditions	
Speed (km/h)	43.2
Angle (deg - veh. c.g.)	10
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	1.3
y-direction	-0.3
Ridedown Acceleration (g's)	
x-direction	-2.2
y-direction	-1.3
European Committee for Normalization (CEN) Values	
THIV (km/h)	5.7
PHD (g's)	2.2
ASI	0.3
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	15.3
Maximum Pitch Angle	29.1
Maximum Yaw Angle	-10.6
Test Article Deflections (m)	
Dynamic	N/A
Permanent	N/A
Vehicle Damage (Primary Impact)	
Exterior	
VDS	N/A
CDC	N/A
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

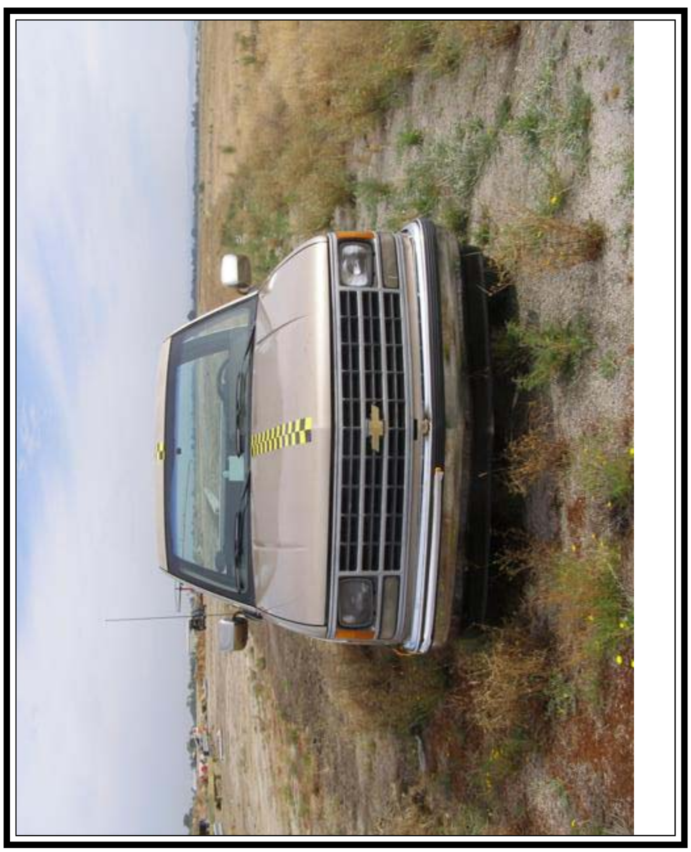
Figure 6. Summary of Results - Florida Curb End Treatment Test 71-1776-005

Figure 7. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-005

Figure 8. Test Article Damage - Florida Curb End Treatment Test 71-1776-005







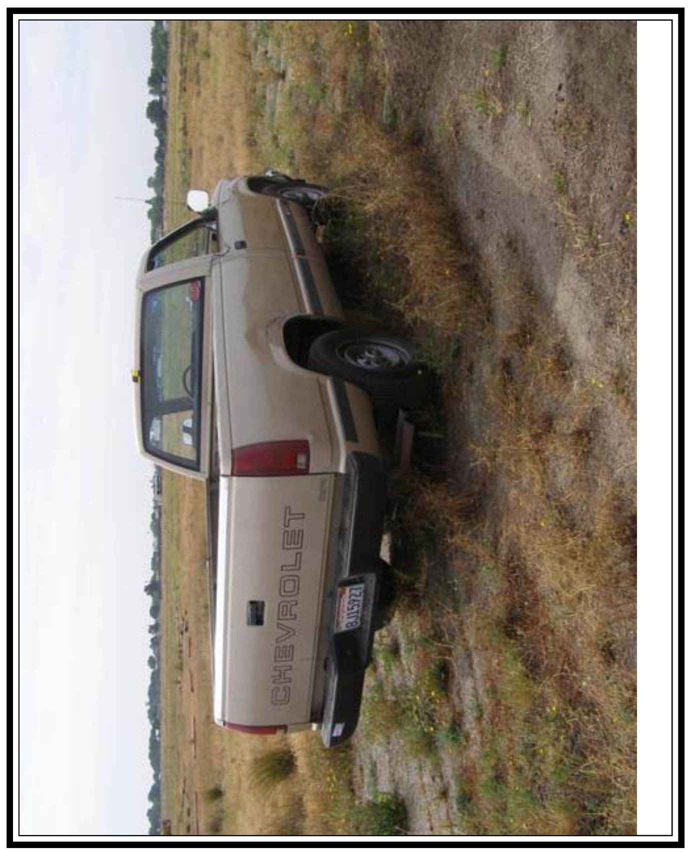


Figure 9. Vehicle Damage - Florida Curb End Treatment Test 71-1776-005

Test No: 71-1776-005

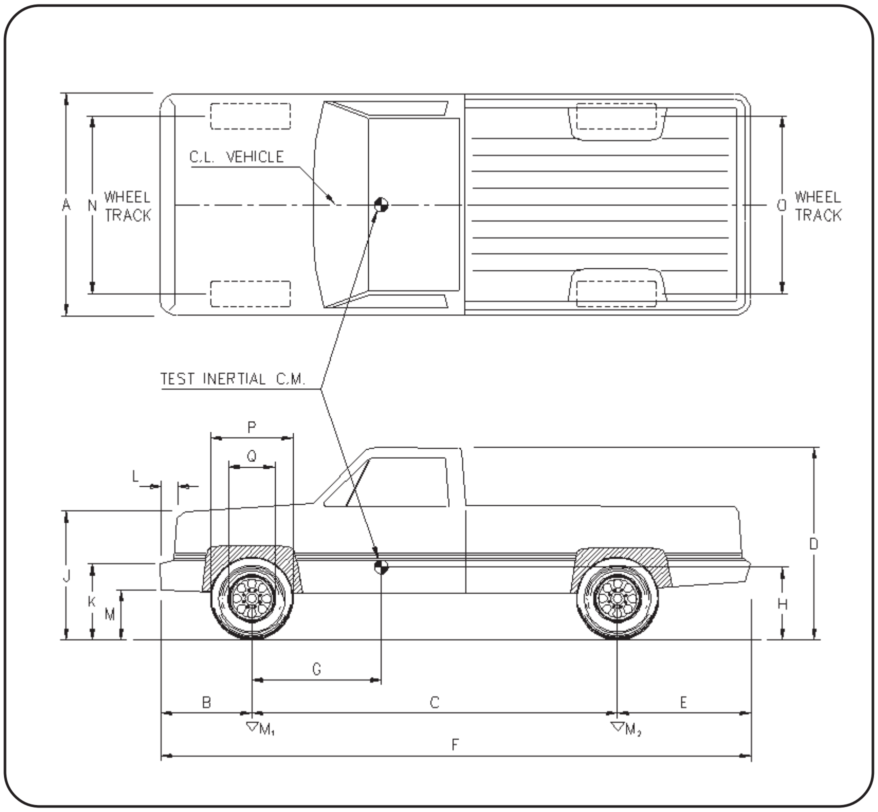
VEHICLE GEOMETRY
2000P

Date: 05/20/08

		Test Inertial Mass Distribution (kg):	
Make:	Chevrolet	**LF**	557
Model:	C2500 Pickup	**RF**	564
Year:	1988	**LR**	445
Odometer:	209483	**RR**	433

Describe any damage to vehicle prior to test:
dent above right rear wheel well

VIN No.
1GCFC24KXJE135449



Engine Type: 8 Cylinder

Engine CID: 5.7 Liter

Transmission Type: Automatic

Optional Equipment: A/C

Dummy Data:

Type: N/A
Mass: N/A
Seat: N/A

Pretest Geometry - cm.

A	190.0	**D**	184.0	**G**	147.1	**K**	60.0	**N**	160.0	**Q**	40.6
B	86.0	**E**	130.0	**H**	66.0	**L**	10.0	**O**	161.0		
C	335.0	**F**	551.0	**J**	100.0	**M**	45.0	**P**	71.0		

Mass - kg	**Curb**	**Test Inertial**	**Gross Static**
M_1	1068	1121	1121
M_2	769	878	878
M_T	1837	1999	1999

Figure 10. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-005

Florida Concrete Curb End Treatment
Test 71-1776-002
(NCHRP 350 Test 2-32)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-002 is summarized in Figure 1. Details of the test article installation are given in Section II.A.2. and Appendix D of this report. The test article exhibited only minor cosmetic damage from earlier test(s) and was essentially functioning as new.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a small 820C passenger vehicle under a 15 deg angled impact centered on the nose of the test article. The test was run on May 8, 2008 using a white 1988 Ford Festiva. The pre-test photographs are shown in Figure 12. The curb mass of the vehicle was 818 kg and the final test inertial mass was 832 kg. A 75 kg anthropomorphic dummy was restrained in the passenger seat. The actual impact conditions were 72.0 km/h and 15 deg. The impact severity was 166.6 kJ which was within the NCHRP 350 recommended tolerance of 154.9 (-17.2 / +18.2) kJ.

The left front tire rolled up on the front side of the end terminal 2.4 m downstream from the nose of the test article . The front tire track was immediately followed by the left rear tire then the vehicle undercarriage contacted the test article. The vehicle pitched up and rolled clockwise then the left side tires momentarily lost contact with the ground. The vehicle lost contact with the test article and was partially redirected then came back down onto all four tires behind the installation. The vehicle exited at an angle of 8 deg relative to installation centerline and a speed of 68.9 km/h when it lost contact with the test article. The vehicle passed behind the test article and did not experience excessive roll, pitch, or yaw. The emergency braking system was applied approximately 20 m after loss of contact and the vehicle skidded to a stop 51.2 m downstream and 10.5 m to the back side of the point of impact. There was no lateral dynamic or permanent deflection of the test article.

The theoretical occupant impact velocity values in the longitudinal and lateral directions were 0.9 and -1.2 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -1.0 and -1.7 g's respectively. The Theoretical Head Impact Velocity (THIV) was 5.4 km/h and the Post-Impact Head Deceleration (PHD) was 1.8 g's. The Acceleration Severity Index (ASI) was 0.3. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 27.5, 6.6, and 10.5 deg respectively.

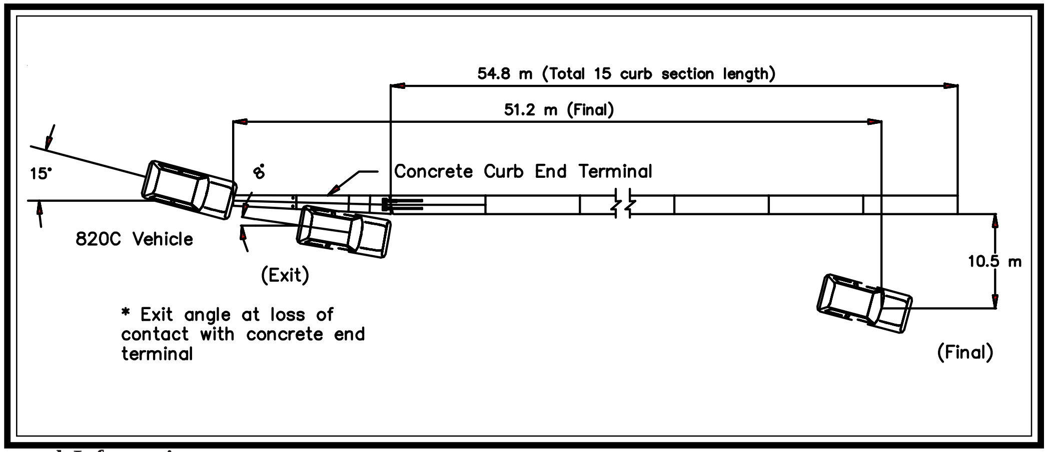
Test Article Damage/Debris Pattern

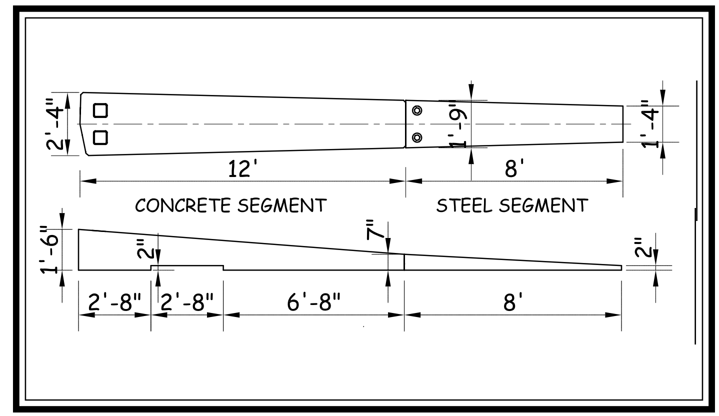
The test article damage is shown in the post-test photographs of Figure 13. There was negligible dynamic and permanent deflection of the test article. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. There was no debris expelled by the test article.

Vehicle Damage

The vehicle damage is shown in Figure 14. There was essentially no damage to the test vehicle other than a flat tire consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC). There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 15.

t = 0.000 sec | t = 0.114 sec | t = 0.228 sec | t = 0.342 sec | t = 0.456 sec | t = 0.570 sec





General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 2-32
Test No.	71-1776-002
Date	5/08/08
Test Article	
Type	University of Florida Concrete Curb End Treatment 6.1 m length
Installation Length	60.9 overall with (15) curbs
Material and key elements	Terminal: (1) 2.4 m long Steel Segment and (1) 3.7 m Concrete Segment, Barrier: (15) 3.7 m Curb Segments
Foundation Type and Condition	Aged chip seal asphalt, dry
Test Vehicle	
Type	Production Model
Designation	820C
Model	1988 Ford Festiva
Mass (kg)	
Curb	818
Test inertial	832
Dummy	75
Gross Static	907
Impact Conditions	
Speed (km/h)	72.0
Angle (deg)	15
Impact Severity (kJ)	166.6

Exit conditions	
Speed (km/h)	68.9
Angle (deg - veh. c.g.)	8
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	0.9
y-direction	-1.2
Ridedown Acceleration (g's)	
x-direction	-1.0
y-direction	-1.7
European Committee for Normalization (CEN) Values	
THIV (km/h)	5.4
PHD (g's)	1.8
ASI	0.3
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	27.5
Maximum Pitch Angle	6.6
Maximum Yaw Angle	10.5
Test Article Deflections (m)	
Dynamic	N/A
Permanent	N/A
Vehicle Damage (Primary Impact)	
Exterior	
VDS	N/A
CDC	N/A
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 11. Summary of Results - Florida Curb End Treatment Test 71-1776-002

Figure 12. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-002

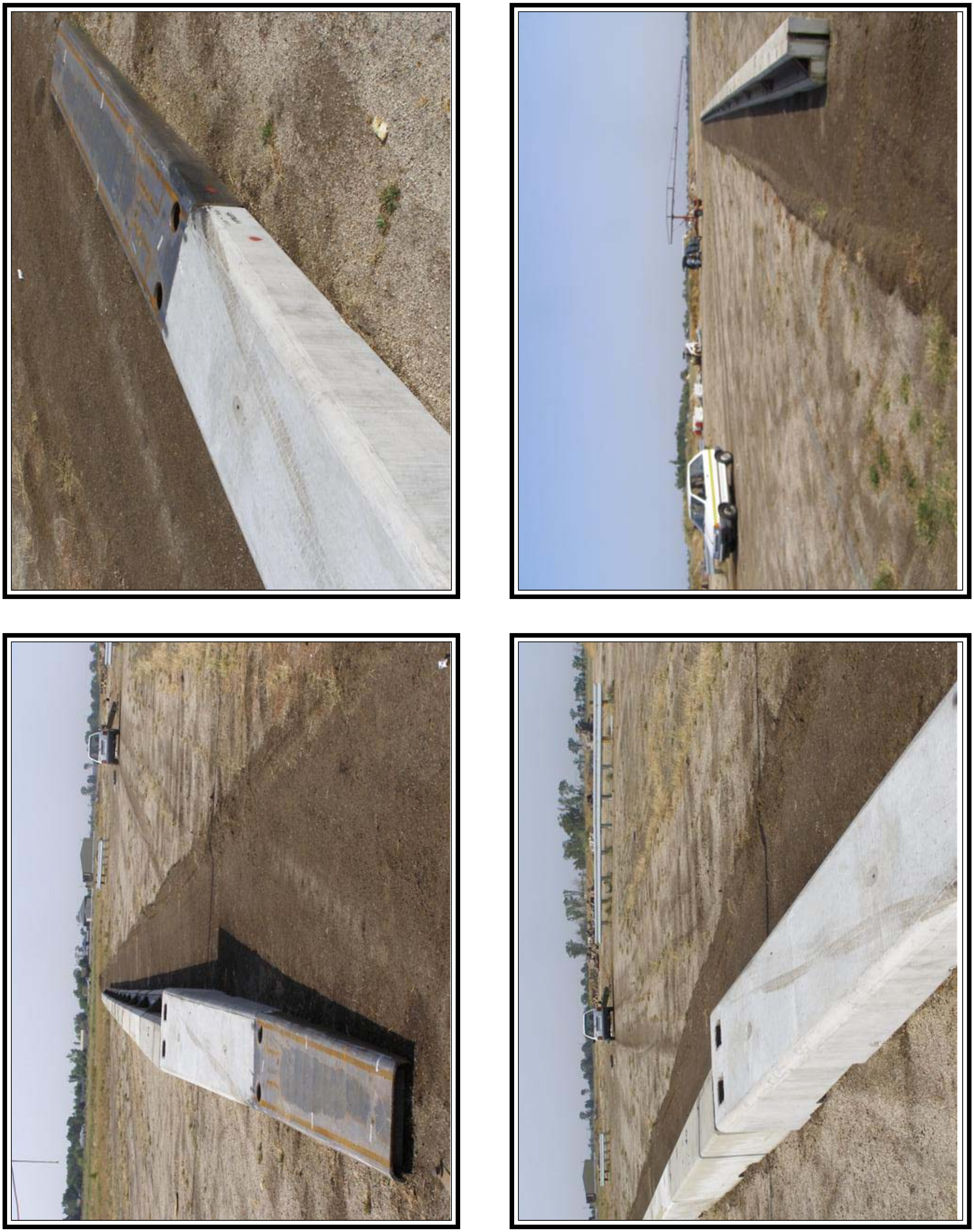


Figure 13. Test Article Damage - Florida Curb End Treatment Test 71-1776-002

Figure 14. Vehicle Damage - Florida Curb End Treatment Test 71-1776-002

Test No: 71-1776-002

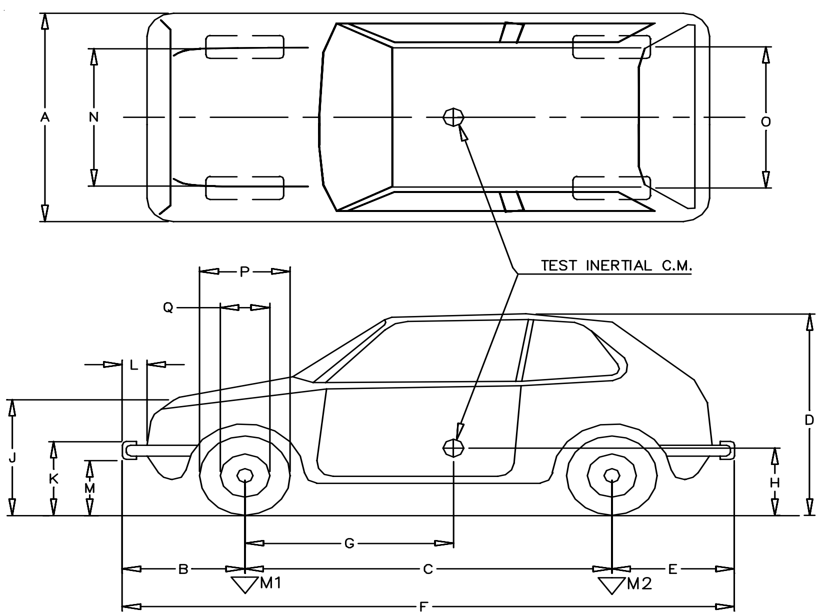
VEHICLE GEOMETRY
820C

Date: 05/08/08

		Test Inertial Mass Distribution (kg):	
Make:	Ford	**LF**	281.5
Model:	Festiva	**RF**	263.0
Year:	1988	**LR**	142.0
Odometer:	231342	**RR**	145.5

Describe any damage to vehicle prior to test:
small dent in rear right panel

VIN No.
KNJBT07K0J6153027



Engine Type: 4 Cylinder

Engine CID: 1.3 Liter

Transmission Type: Manual

Optional Equipment: a.c.

Dummy Data:

Type: Anthropomorphic
Mass: 75 kg
Seat: Passenger

Pretest Geometry - cm.

A	160.0	**D**	142.0	**G**	77.7	**K**	53.0	**N**	140.0	**Q**	30.7
B	58.0	**E**	68.0	**H**	45.0	**L**	10.0	**O**	138.0		
C	225.0	**F**	351.0	**J**	70.0	**M**	40.0	**P**	54.0		

Mass - kg	**Curb**	**Test Inertial**	**Gross Static**
M_1	533	544	593
M_2	285	288	314
M_T	818	832	907

Figure 15. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-002

Florida Concrete Curb End Treatment
Test 71-1776-001
(NCHRP 350 Test 2-33)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-001 is summarized in Figure 16. Details of the test article installation are given in Section II.A.2. and Appendix D of this report.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a large 2000P passenger vehicle under a 15 deg angled impact centered on the nose of the test article. The test was run on April 29, 2008 using a silver 1989 Chevrolet C2500 pickup truck. The pre-test photographs are shown in Figure 17. The curb mass of the vehicle was 1883 kg and the final test inertial mass was 2000 kg. The actual impact conditions were 73.1 km/h and 15 deg. The impact severity was 412.6 kJ which was near the high range of the NCHRP 350 recommended tolerance of 377.9 (-41.9 / +44.4) kJ.

The left front tire rolled up on the front side of the end terminal near the connection between the first and second sections then was immediately followed by the left rear tire. The vehicle undercarriage did not make contact with the test article. The vehicle momentarily lost contact with the ground, rolled slightly, then lost contact with the test article and exited at an angle of 13 deg relative to installation centerline. The vehicle passed behind the test article and did not experience excessive roll, pitch, or yaw. The vehicle was traveling 69.5 km/h when it lost contact with the test article. The emergency braking system was applied approximately 15 m after loss of contact and the vehicle skidded to a stop 63.0 m downstream and 16.5 to the back side of the point of impact. There was no lateral dynamic or permanent deflection of the test article.

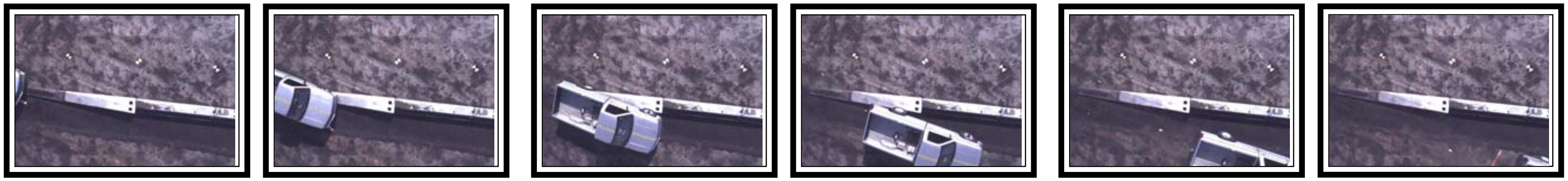
The theoretical occupant impact velocity values in the longitudinal and lateral directions were 1.0 and -0.5 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -1.6 and -1.4 g's respectively. The Theoretical Head Impact Velocity (THIV) was 5.4 km/h and the Post-Impact Head Deceleration (PHD) was 1.6 g's. The Acceleration Severity Index (ASI) was 0.3. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 8.7, 8.8, and 15.2 deg respectively.

Test Article Damage/Debris Pattern

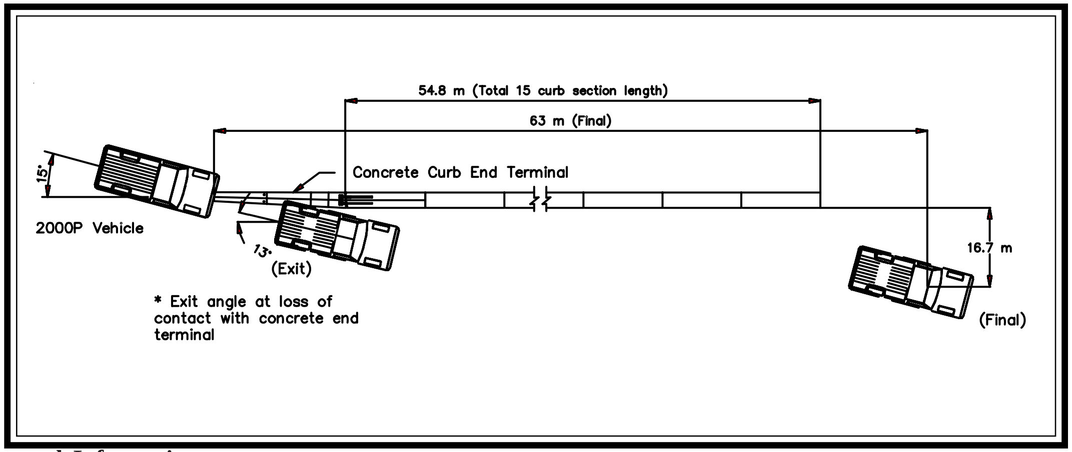
The test article damage is shown in the post-test photographs of Figure 18. There was negligible dynamic and permanent deflection of the test article. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. There was no debris expelled by the test article.

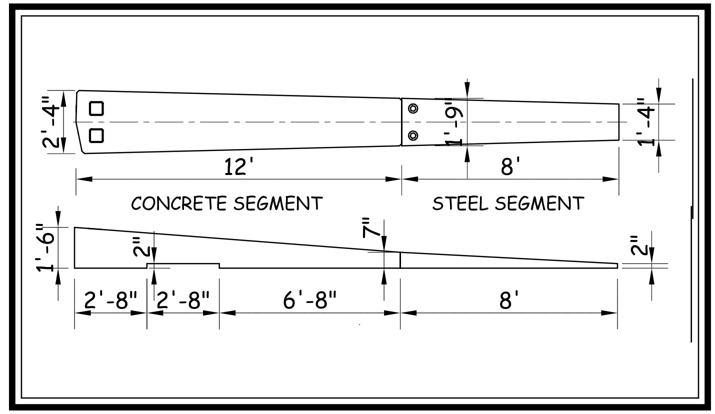
Vehicle Damage

Post test photographs of the vehicle are shown in Figure 19. There was essentially no damage to the test vehicle consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC). There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 20.



t = 0.000 sec | t = 0.152 sec | t = 0.304 sec | t = 0.456 sec | t = 0.608 sec | t = 0.760 sec





General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 2-33
Test No.	71-1776-001
Date	4/29/08
Test Article	
Type	University of Florida
	Concrete Curb End Treatment
	6.1 m length
Installation Length	60.9 overall with (15) curbs
Material and key elements	Terminal: (1) 2.4 m long Steel
	Segment and (1) 3.7 m Concrete
	Segment, Barrier: (15) 3.7 m Curb
	Segments
Foundation Type and Condition	Aged chip seal asphalt, dry
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1989 Chevrolet C2500
	3/4 Ton Pickup
Mass (kg)	
Curb	1883
Test inertial	2000
Dummy	N/A
Gross Static	2000
Impact Conditions	
Speed (km/h)	73.1
Angle (deg)	15
Impact Severity (kJ)	412.6

Exit conditions	
Speed (km/h)	69.5
Angle (deg - veh. c.g.)	13
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	1.0
y-direction	-0.5
Ridedown Acceleration (g's)	
x-direction	-1.6
y-direction	-1.4
European Committee for Normalization (CEN) Values	
THIV (km/h)	5.4
PHD (g's)	1.6
ASI	0.3
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	8.7
Maximum Pitch Angle	8.8
Maximum Yaw Angle	15.2
Test Article Deflections (m)	
Dynamic	N/A
Permanent	N/A
Vehicle Damage (Primary Impact)	
Exterior	
VDS	N/A
CDC	N/A
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 16. Summary of Results - Florida Curb End Treatment Test 71-1776-001

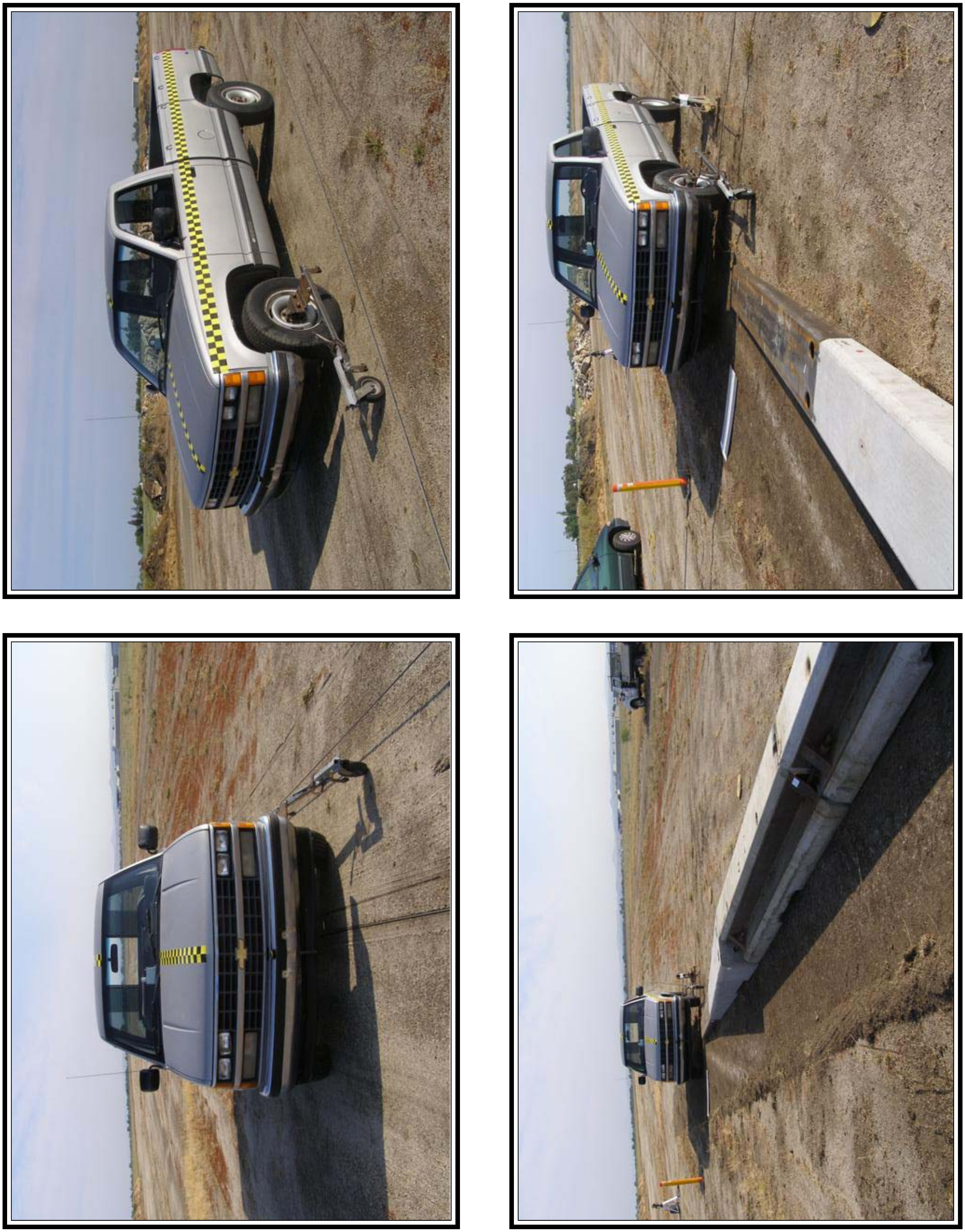
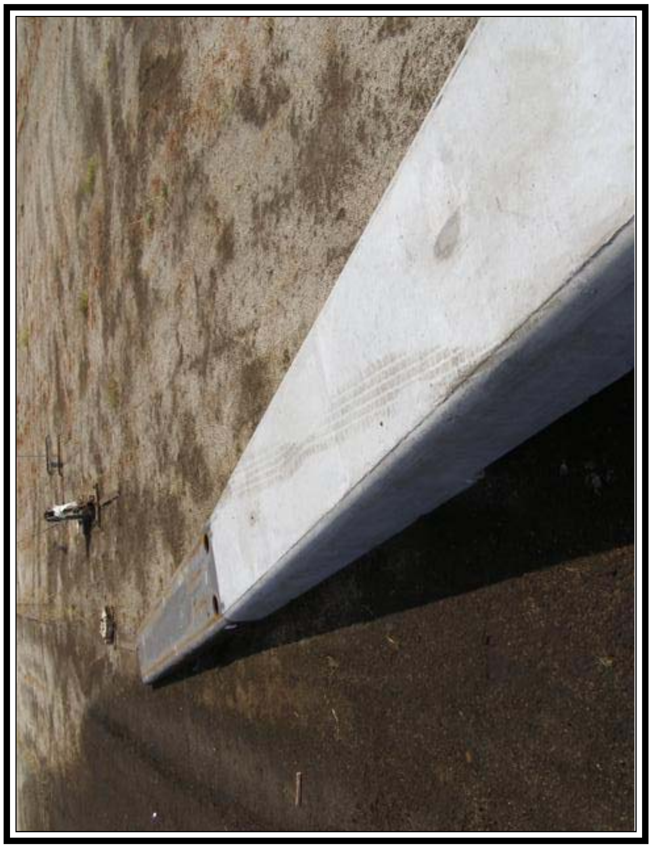


Figure 17. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-001



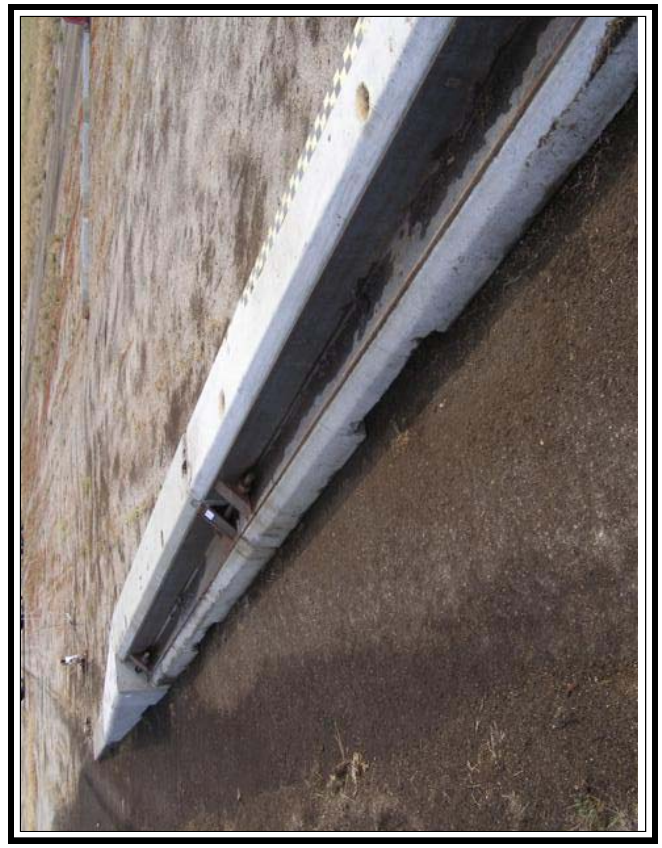


Figure 18. Test Article Damage - Florida Curb End Treatment Test 71-1776-001

Figure 19. Vehicle Damage - Florida Curb End Treatment Test 71-1776-001

VEHICLE GEOMETRY 2000P

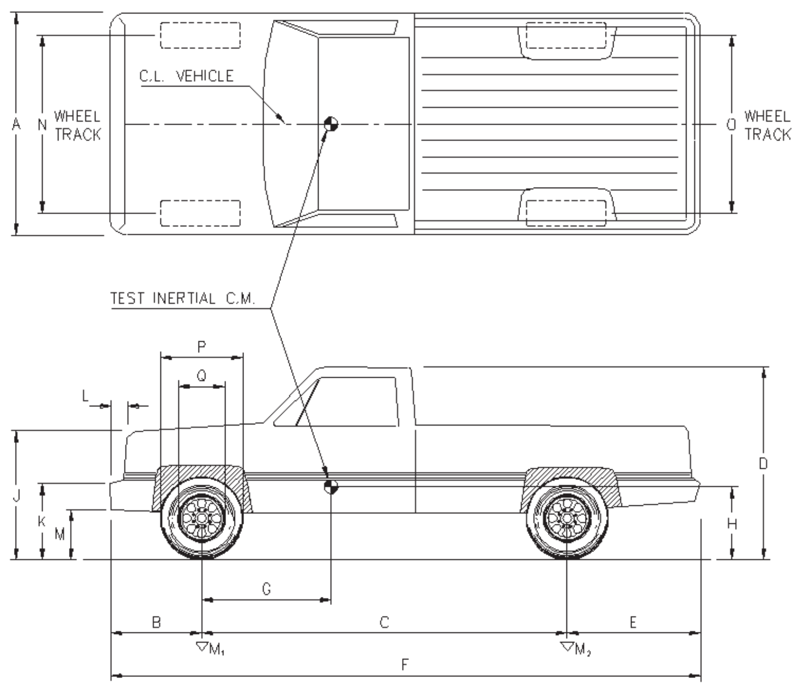
Test No: 71-1776-001

Date: 04/29/08

		Test Inertial Mass Distribution (kg):	
Make:	Chevrolet	**LF**	577
Model:	C2500 Pickup	**RF**	555
Year:	1989	**LR**	432
Odometer:	220837	**RR**	436

Describe any damage to vehicle prior to test:
none

VIN No.
1GCFC24K24H1KE16031



Engine Type: 8 Cylinder

Engine CID: 5.0 Liter

Transmission Type: Automatic

Optional Equipment: A/C

Dummy Data:

Type: N/A
Mass: N/A
Seat: N/A

Pretest Geometry - cm.

A	190.0	**D**	184.0	**G**	145.4	**K**	61.0	**N**	160.0	**Q**	40.7
B	86.0	**E**	130.0	**H**	70.0	**L**	10.0	**O**	161.0		
C	335.0	**F**	551.0	**J**	100.0	**M**	45.0	**P**	73.0		

Mass - kg	Curb	Test Inertial	Gross Static
M_1	1096	1132	1132
M_2	787	868	868
M_T	1883	2000	2000

Figure 20. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-001

Florida Concrete Curb End Treatment Test 71-1776-003 (NCHRP 350 Test 2-34)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-003 is summarized in Figure 21. Details of the test article installation are given in Section II.A.2. and Appendix D of this report. The test article exhibited only minor cosmetic damage from earlier test(s) and was essentially functioning as new.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a small 820C passenger vehicle under an angled impact into the critical impact point (CIP) near the nose of the test article. The test was run on May 13, 2008 using a white 1988 Ford Festiva. The pre-test photographs are shown in Figure 22. The curb mass of the vehicle was 818 kg and the final test inertial mass was 832 kg. A 75 kg anthropomorphic dummy was restrained in the passenger seat. The actual impact conditions were 71.7 km/h and 15 deg. The impact severity was 11.0 kJ which was within the NCHRP 350 recommended tolerance of 10.4 (-1.2 / +1.2) kJ.

The right front tire rolled up on the front side of the end terminal 2.1 m downstream from the nose of the test article then blew out. The front tire track was immediately followed by the right rear tire then the vehicle undercarriage contacted the test article. The vehicle pitched up and momentarily lost contact with the ground. The vehicle was partially redirected then came back down onto the downstream curb sections. The vehicle skidded along the top of four downstream curb sections then rolled off the back side of the curb, came back into contact with the ground, and lost contact with the test article. The vehicle exited at an angle of 5 deg relative to installation centerline and a speed of 64.8 km/h when it lost contact with the test article. The vehicle passed behind the test article and did not experience excessive roll, pitch, or yaw. The emergency braking system was applied approximately 20 m after loss of contact and the vehicle skidded to a stop 68.4 m downstream and 1.5 m to the back side of the point of impact. There was no lateral dynamic or permanent deflection of the test article.

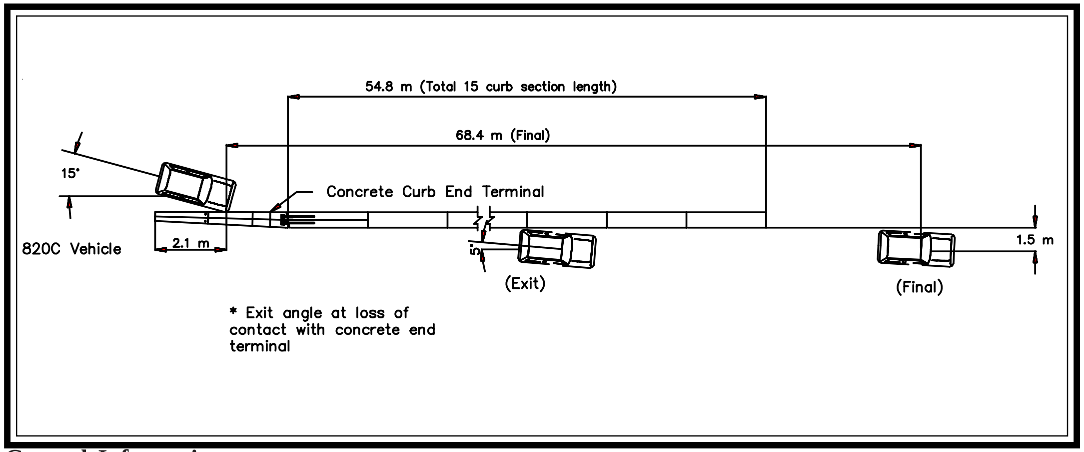
The theoretical occupant impact velocity values in the longitudinal and lateral directions were 1.7 and -2.1 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -1.7 and -6.0 g's respectively. The Theoretical Head Impact Velocity (THIV) was 9.8 km/h and the Post-Impact Head Deceleration (PHD) was 6.0 g's. The Acceleration Severity Index (ASI) was 0.5. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 33.2, 9.2, and -24.4 deg respectively.

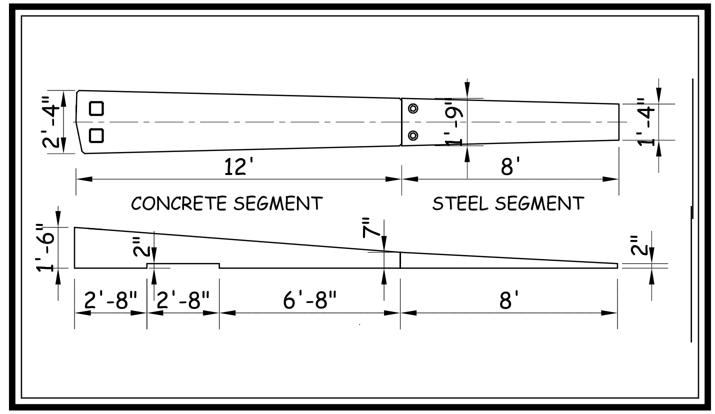
Test Article Damage/Debris Pattern

The test article damage is shown in the post-test photographs of Figure 23. There was negligible dynamic and permanent deflection of the test article. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. There was no debris expelled by the test article.

Vehicle Damage

The vehicle damage is shown in Figure 24. There was essentially no damage to the test vehicle other than a flat tire consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC). There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 25.

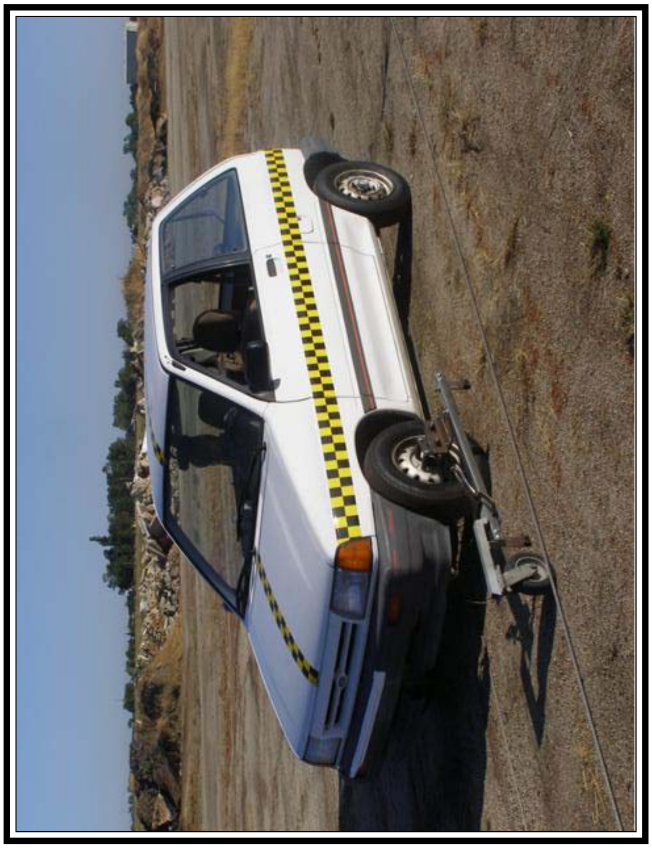


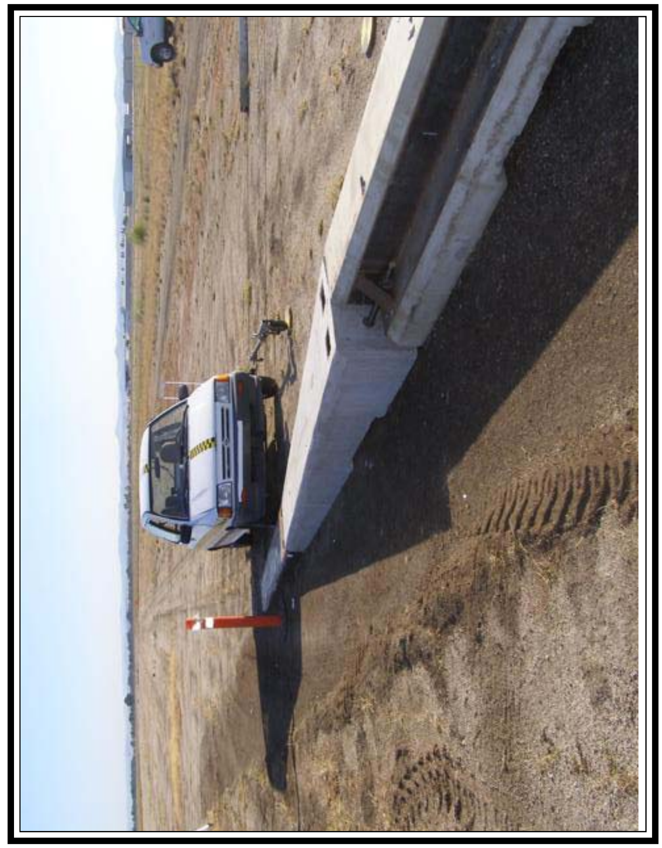


General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 2-34
Test No.	71-1776-003
Date	5/13/08
Test Article	
Type	University of Florida Concrete Curb End Treatment 6.1 m length
Installation Length	60.9 overall with (15) curbs
Material and key elements	Terminal: (1) 2.4 m long Steel Segment and (1) 3.7 m Concrete Segment, Barrier: (15) 3.7 m Curb Segments
Foundation Type and Condition	Aged chip seal asphalt, dry
Test Vehicle	
Type	Production Model
Designation	820C
Model	1988 Ford Festiva
Mass (kg)	
Curb	818
Test inertial	832
Dummy	75
Gross Static	907
Impact Conditions	
Speed (km/h)	71.7
Angle (deg)	15
Impact Severity (kJ)	11.0

Exit conditions	
Speed (km/h)	64.8
Angle (deg - veh. c.g.)	5
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	1.7
y-direction	-2.1
Ridedown Acceleration (g's)	
x-direction	-1.7
y-direction	-6.0
European Committee for Normalization (CEN) Values	
THIV (km/h)	9.8
PHD (g's)	6.0
ASI	0.5
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	33.2
Maximum Pitch Angle	9.2
Maximum Yaw Angle	-24.4
Test Article Deflections (m)	
Dynamic	N/A
Permanent	N/A
Vehicle Damage (Primary Impact)	
Exterior	
VDS	N/A
CDC	N/A
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 21. Summary of Results - Florida Curb End Treatment Test 71-1776-003





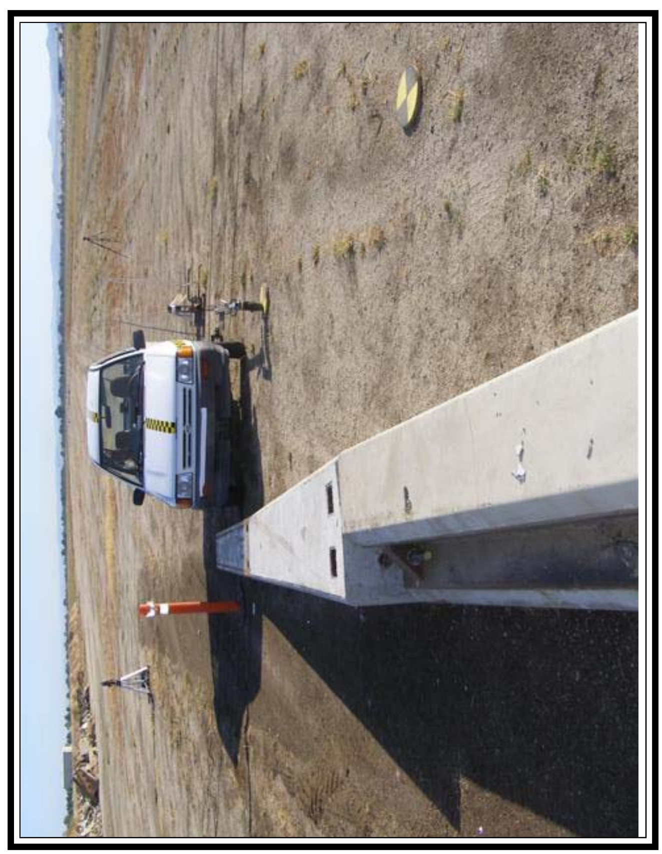


Figure 22. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-003

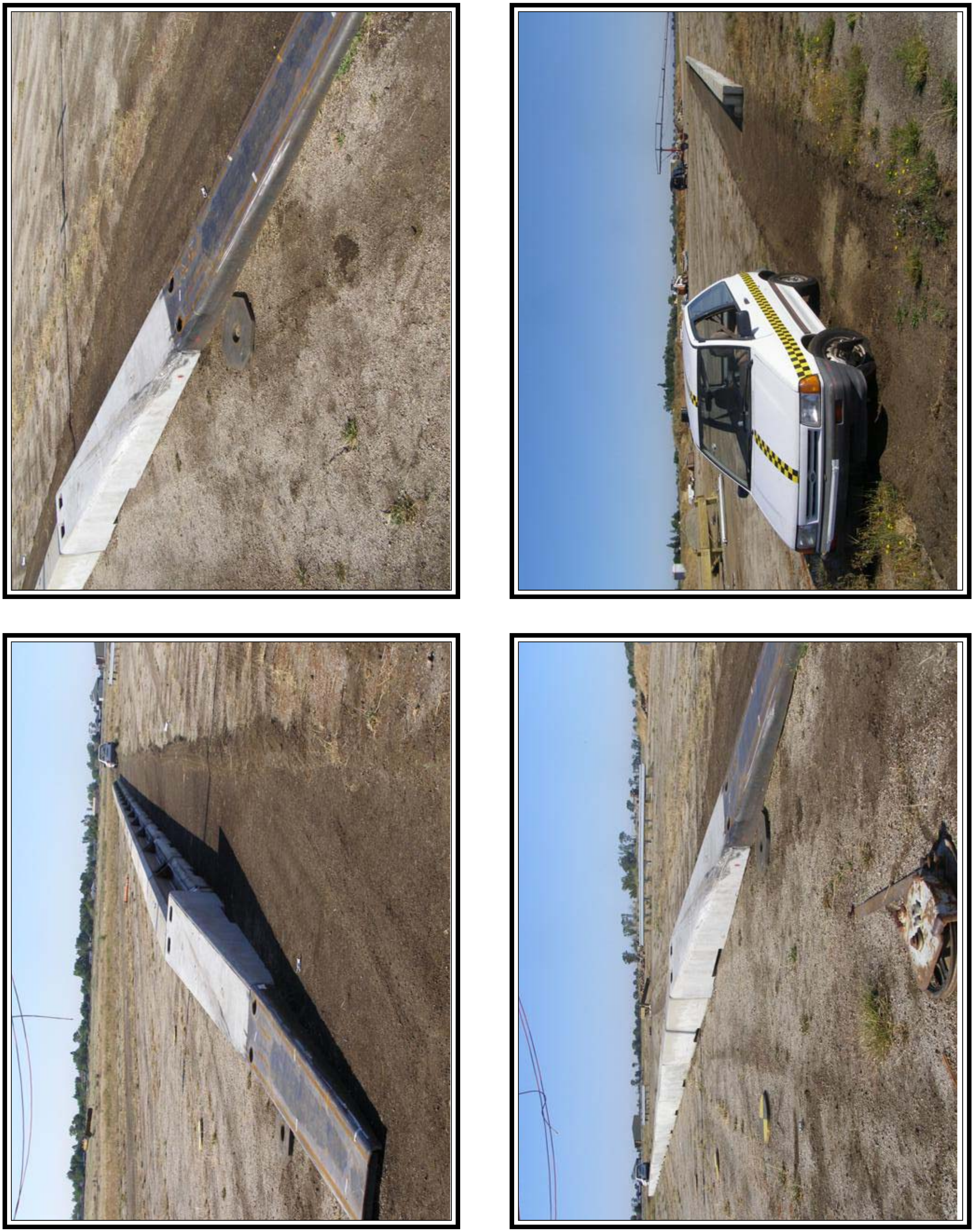


Figure 23. Test Article Damage - Florida Curb End Treatment Test 71-1776-003

Figure 24. Vehicle Damage - Florida Curb End Treatment Test 71-1776-003

Test No: 71-1776-003

VEHICLE GEOMETRY 820C

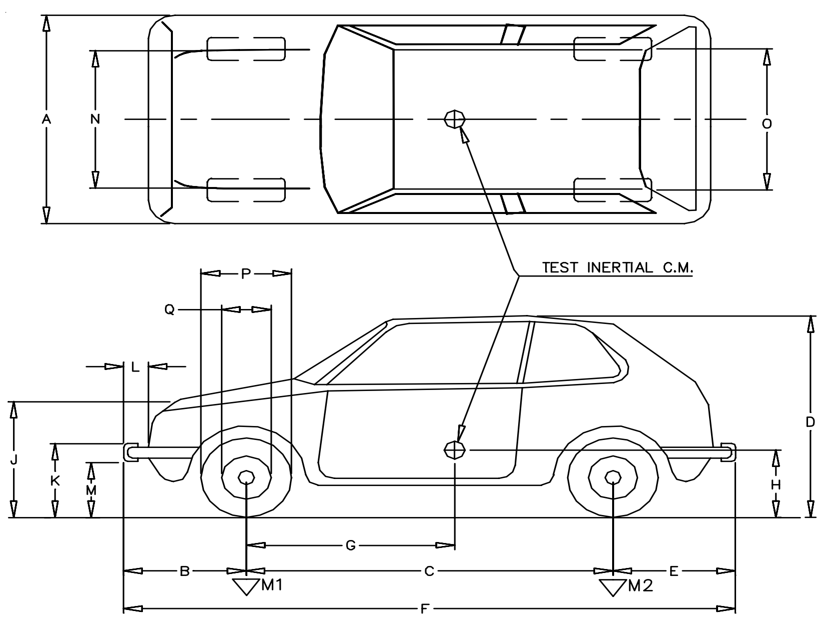
Date: 05/13/08

Test Inertial Mass Distribution (kg):

Make:	Ford	**LF**	281.5
Model:	Festiva	**RF**	263.0
Year:	1988	**LR**	142.0
Odometer:	231342	**RR**	145.5

Describe any damage to vehicle prior to test:
small dent in rear right panel

VIN No.
KNJBT07K0J6153027



Engine Type: 4 Cylinder

Engine CID: 1.3 Liter

Transmission Type: Manual

Optional Equipment: a.c.

Dummy Data:

Type: Anthropomorphic
Mass: 75 kg
Seat: Passenger

Pretest Geometry - cm.

A	160.0	**D**	142.0	**G**	77.7	**K**	53.0	**N**	140.0	**Q**	30.7
B	58.0	**E**	68.0	**H**	45.0	**L**	10.0	**O**	138.0		
C	225.0	**F**	351.0	**J**	70.0	**M**	40.0	**P**	54.0		

Mass - kg	**Curb**	**Test Inertial**	**Gross Static**
M_1	533	544	593
M_2	285	288	314
M_T	818	832	907

Figure 25. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-003

Florida Concrete Curb End Treatment
Test 71-1776-006
(NCHRP 350 Test 2-35)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-006 is summarized in Figure 26. Details of the test article installation are given in Section II.A.2. and Appendix D of this report. The test article exhibited only minor cosmetic damage from earlier test(s) and was essentially functioning as new.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a large 2000P passenger vehicle under an angled impact into the beginning of the length of need 6.1 m from the nose of the test article. The test was run on May 29, 2008 using a white 1993 GMC C2500 pickup truck. The pre-test photographs are shown in Figure 27. The curb mass of the vehicle was 1877 kg and the final test inertial mass was 2013 kg. The actual impact conditions were 72.4 km/h and 20 deg. The impact severity was 47.6 kJ which was near the high range of the NCHRP 350 recommended tolerance of 44.2 (-4.9 / +5.2) kJ.

The right front tire contacted the front face of the end installation. 75 mm past the connection between the End Terminal and first downstream curb then was immediately followed by the right rear tire. The vehicle was redirected and momentarily lost contact with the ground and rolled slightly. The vehicle came back down and slid down the curb then lost contact with the test article and exited at an angle of 19 deg relative to installation centerline. The vehicle did not experience excessive roll, pitch, or yaw. The vehicle was traveling 52.3 km/h when it lost contact with the test article. The emergency braking system was applied approximately 10 m after loss of contact and the vehicle skidded to a stop 75.0 m downstream and 9.7 to the back side of the point of impact.

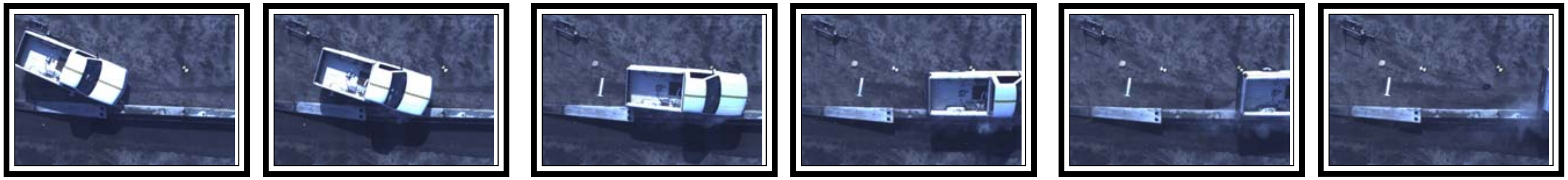
The theoretical occupant impact velocity values in the longitudinal and lateral directions were 3.0 and -3.9 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -3.3 and -7.5 g's respectively. The Theoretical Head Impact Velocity (THIV) was 17.3 km/h and the Post-Impact Head Deceleration (PHD) was 7.5 g's. The Acceleration Severity Index (ASI) was 0.6. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 21.5, -5.8, and -47.2 deg respectively.

Test Article Damage/Debris Pattern

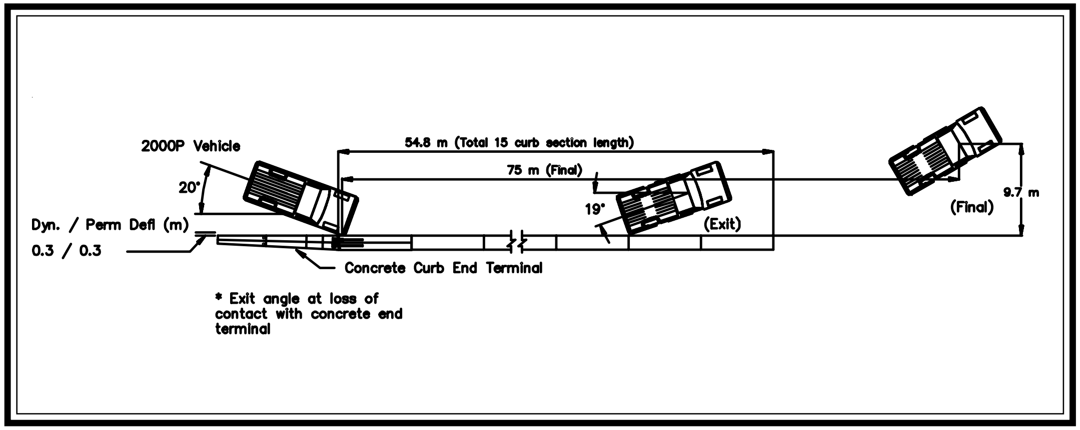
The test article damage is shown in the post-test photographs of Figure 28. The maximum lateral dynamic/ permanent deflection of the test article was 0.3 m as measured from the front steel segment. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. There was no debris expelled by the test article.

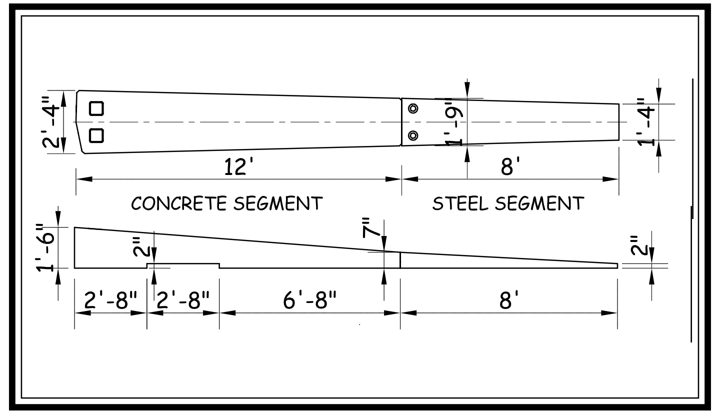
Vehicle Damage

Post test photographs of the vehicle are shown in Figure 29. There was essentially no damage to the test vehicle consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC). There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 30.



t = 0.000 sec | t = 0.117 sec | t = 0.234 sec | t = 0.351 sec | t = 0.468 sec | t = 0.585 sec





General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 2-35
Test No.	71-1776-006
Date	5/29/08
Test Article	
Type	University of Florida
	Concrete Curb End Treatment
	6.1 m length
Installation Length	60.9 overall with (15) curbs
Material and key elements	Terminal: (1) 2.4 m long Steel
	Segment and (1) 3.7 m Concrete
	Segment, Barrier: (15) 3.7 m Curb
	Segments
Foundation Type and Condition	Aged chip seal asphalt, dry
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1993 Chevrolet C2500
	3/4 Ton Pickup
Mass (kg)	
Curb	1877
Test inertial	2013
Dummy	N/A
Gross Static	2013
Impact Conditions	
Speed (km/h)	72.4
Angle (deg)	20
Impact Severity (kJ)	47.6

Exit conditions	
Speed (km/h)	52.3
Angle (deg - veh. c.g.)	19
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	3.0
y-direction	-3.9
Ridedown Acceleration (g's)	
x-direction	-3.3
y-direction	-7.5
European Committee for Normalization (CEN) Values	
THIV (km/h)	17.4
PHD (g's)	7.5
ASI	0.6
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	21.5
Maximum Pitch Angle	-5.8
Maximum Yaw Angle	-47.2
Test Article Deflections (m)	
Dynamic	0.3
Permanent	0.3
Vehicle Damage (Primary Impact)	
Exterior	
VDS	N/A
CDC	N/A
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 26. Summary of Results - Florida Curb End Treatment Test 71-1776-006

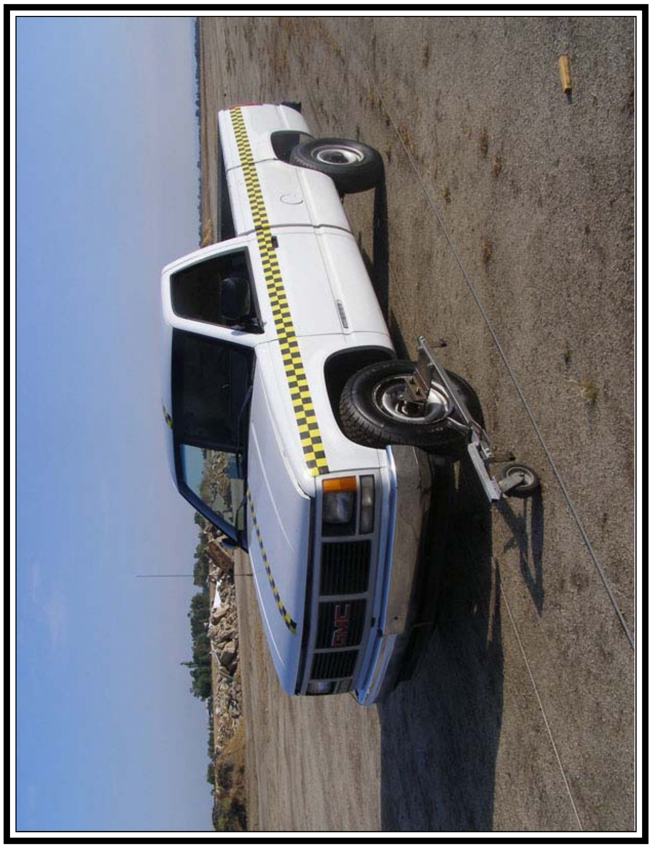


Figure 27. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-006

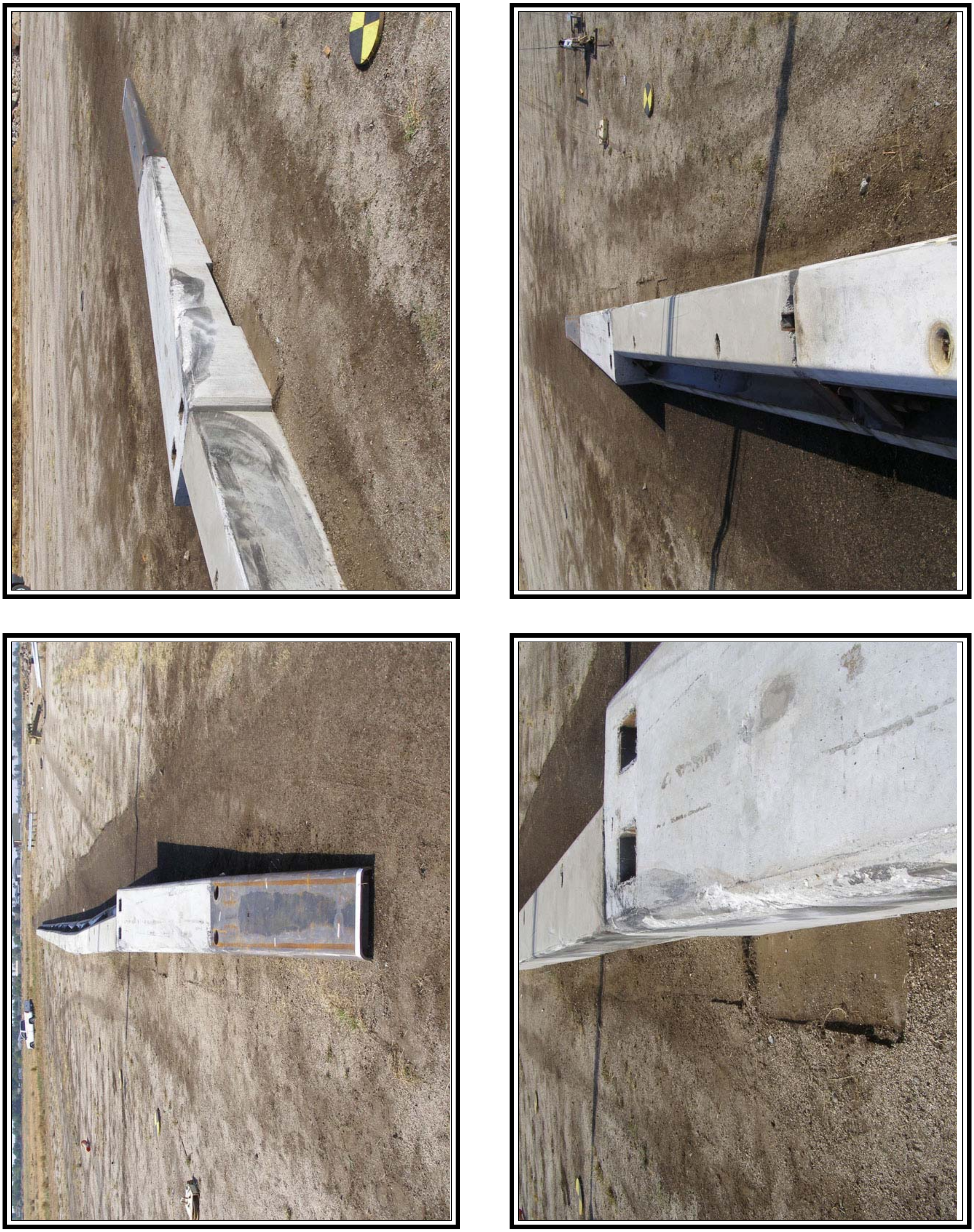
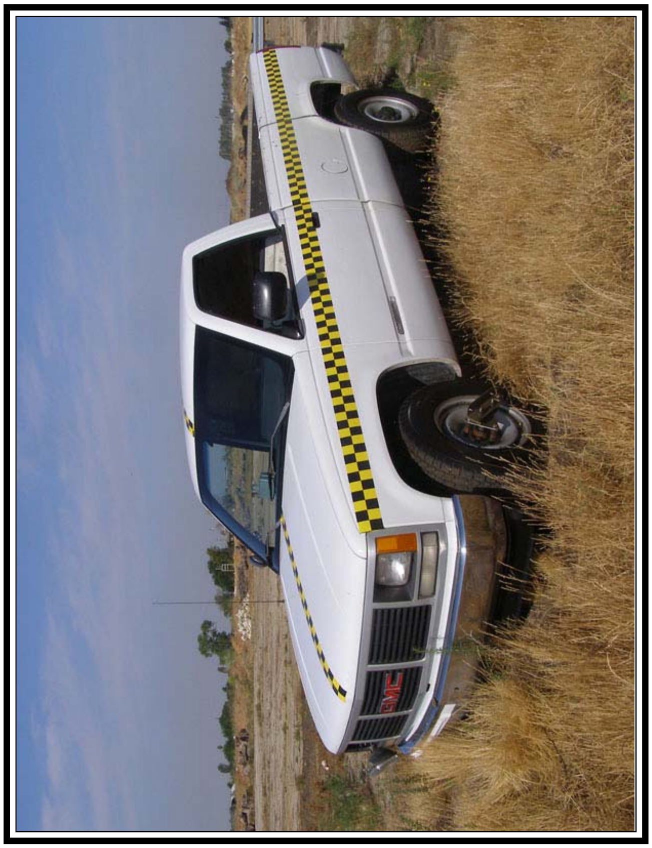


Figure 28. Test Article Damage - Florida Curb End Treatment Test 71-1776-006



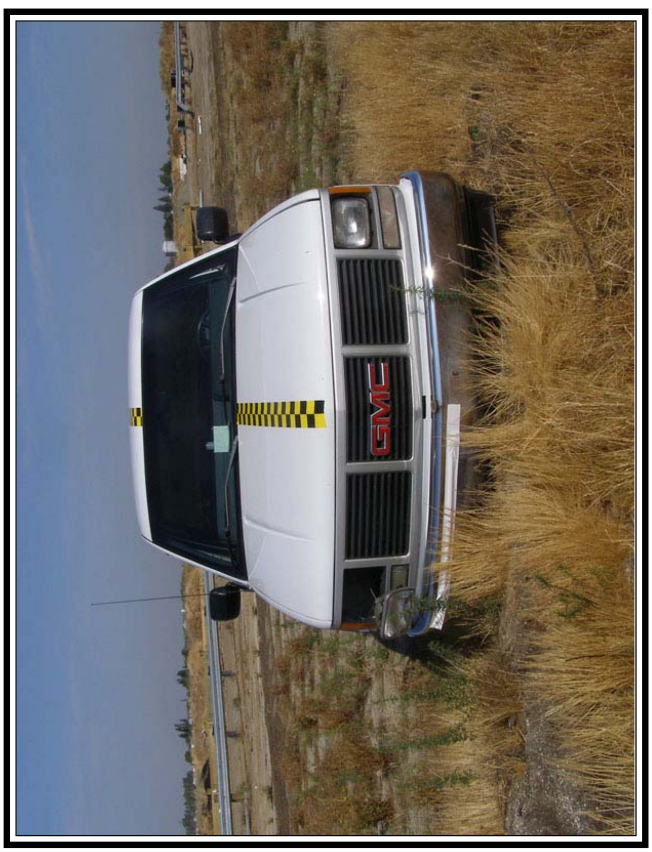


Figure 29. Vehicle Damage - Florida Curb End Treatment Test 71-1776-006

Test No: 71-1776-006

VEHICLE GEOMETRY 2000P

Date: 05/29/08

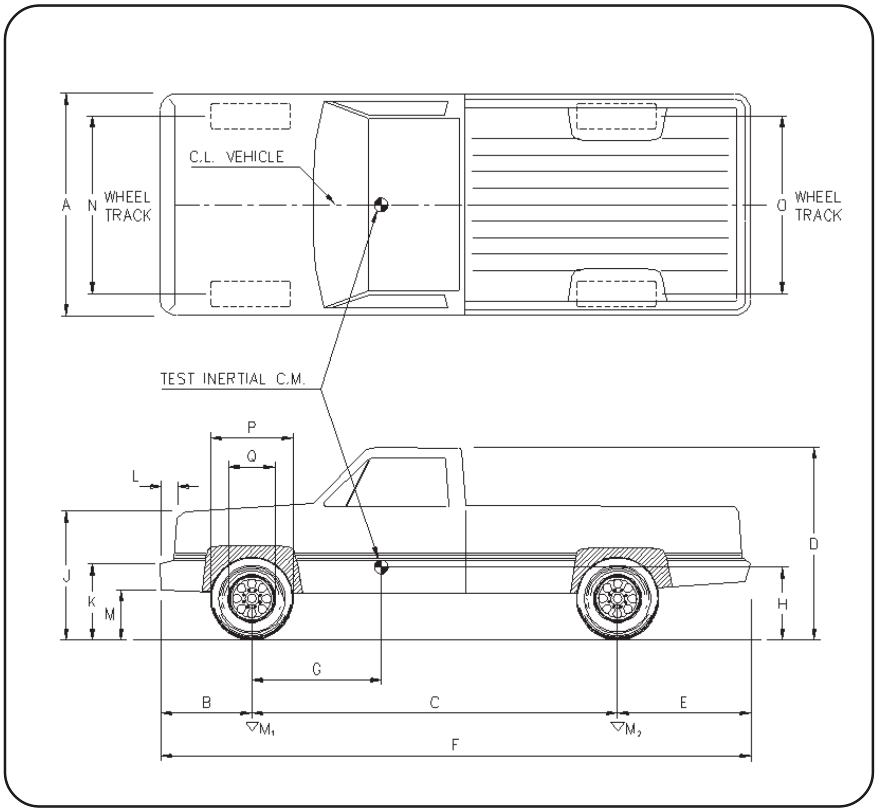
		Test Inertial Mass Distribution (kg):	
Make:	GMC	**LF**	548
Model:	C2500 Pickup	**RF**	555
Year:	1993	**LR**	463
Odometer:	177381	**RR**	447

Describe any damage to vehicle prior to test:

dent on rear passenger fenderwell

VIN No.

1GTFC24K3PE545793



Engine Type: 8 Cylinder

Engine CID: 5.0 Liter

Transmission Type: Automatic

Optional Equipment: A/C

Dummy Data:

Type: N/A
Mass: N/A
Seat: N/A

Pretest Geometry - cm.

A	190.0	**D**	184.0	**G**	151.4	**K**	60.0	**N**	161.0	**Q**	40.7
B	86.0	**E**	130.0	**H**	70.0	**L**	10.0	**O**	160.0		
C	335.0	**F**	551.0	**J**	105.0	**M**	45.0	**P**	72.0		

Mass - kg	Curb	Test Inertial	Gross Static
M_1	1073	1103	1103
M_2	804	910	910
M_T	1877	2013	2013

Figure 30. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-006

Florida Concrete Curb End Treatment
Test 71-1776-007
(NCHRP 350 Test 2-39)

Impact Conditions/Vehicle Behavior

E-TECH Test 71-1776-007 is summarized in Figure 31. Details of the test article installation are given in Section II.A.2. and Appendix D of this report. The test article exhibited only minor cosmetic damage from earlier test(s) and was essentially functioning as new.

The purpose of this test was to evaluate occupant risk and vehicle trajectory criteria for a large 2000P passenger vehicle under a "reverse" angled impact. The test was run on June 12, 2008 using a red 1988 Chevrolet C2500 pickup truck. The pre-test photographs are shown in Figure 32. The curb mass of the vehicle was 1893 kg and the final test inertial mass was 2000 kg. The actual impact conditions were 71.3 km/h and 20 deg reverse angle. The impact severity was 45.9 kJ which was within the NCHRP 350 recommended tolerance of 44.2 (-4.9 / +5.2) kJ.

The left front tire contacted the front side of the end terminal 3.0 m upstream of the end then was immediately followed by the left rear tire. Both tires lost air pressure. The vehicle undercarriage did not make contact with the test article. The vehicle crossed over the installation, rolled slightly, then lost contact with the test article and exited the back side at an angle of 19 deg relative to installation centerline. The vehicle passed behind the test article and did not experience excessive roll, pitch, or yaw. The vehicle was traveling 68.1 km/h when it lost contact with the test article. The emergency braking system was applied approximately 10 m after loss of contact and the vehicle skidded to a stop 18.6 m downstream and 32.8 to the back side of the point of impact.

The theoretical occupant impact velocity values in the longitudinal and lateral directions were 0.9 and -1.0 m/s respectively. The theoretical occupant ridedown acceleration values in the longitudinal and lateral directions were -1.0 and -1.6 g's respectively. The Theoretical Head Impact Velocity (THIV) was 5.4 km/h and the Post-Impact Head Deceleration (PHD) was 1.8 g's. The Acceleration Severity Index (ASI) was 0.3. The maximum roll, pitch, and yaw angles relative to a reference frame at the vehicle center of gravity were 4.1, -4.3, and -29.1 deg respectively.

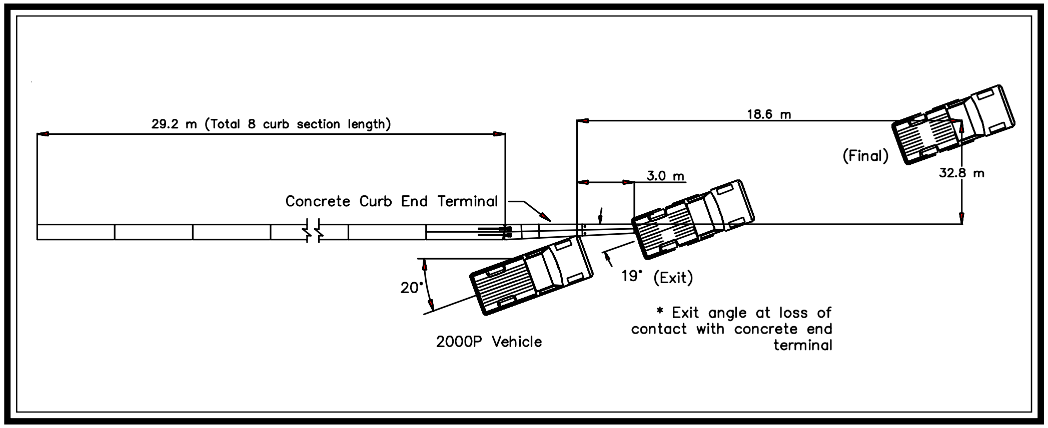
Test Article Damage/Debris Pattern

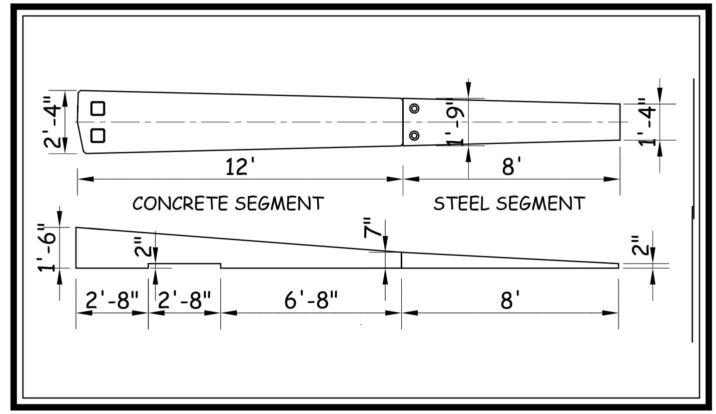
The test article damage is shown in the post-test photographs of Figure 33. According to the FHWA July 97 memorandum, test article damage was categorized as "Category A. None" and no replacement parts would be needed for repair. There was no debris expelled by the test article.

Vehicle Damage

Post test photographs of the vehicle are shown in Figure 34. There was essentially no damage to the test vehicle other than flat tires and suspension damage consequently the damage was categorized as not applicable (N/A) on the Vehicle Damage Scale (VDS) and the Collision Deformation Classification Scale (CDC). There was negligible deformation of the occupant compartment based upon pre- and post-test measurements. The Occupant Compartment Deformation Index (OCDI) was categorized as AS0000000. The pre-test vehicle geometries are shown in Figure 35.

t = 0.000 sec | t = 0.100 sec | t = 0.200 sec | t = 0.300 sec | t = 0.400 sec | t = 0.500 sec





General Information		**Exit conditions**	
Test Agency	E-TECH Testing Services, Inc.	Speed (km/h)	68.1
Test Designation	NCHRP 350 Test 2-39	Angle (deg - veh. c.g.)	19
Test No.	71-1776-007	**Occupant Risk Values**	
Date	6/12/08	Impact Velocity (m/s)	
Test Article		x-direction	0.9
Type	University of Florida Concrete Curb End Treatment 6.1 m length	y-direction	-1.0
Installation Length	35.3 m overall with (8) curbs	Ridedown Acceleration (g's)	
Material and key elements	Terminal: (1) 2.4 m long Steel Segment and (1) 3.7 m Concrete Segment, Barrier: (8) 3.7 m Curb Segments	x-direction	-1.0
		y-direction	-1.6
		European Committee for Normalization (CEN) Values	
		THIV (km/h)	5.4
		PHD (g's)	1.8
		ASI	0.3
Foundation Type and Condition	Aged chip seal asphalt, dry	**Post-Impact Vehicular Behavior (deg - rate gyro)**	
Test Vehicle		Maximum Roll Angle	4.1
Type	Production Model	Maximum Pitch Angle	-4.3
Designation	2000P	Maximum Yaw Angle	-29.1
Model	1988 Chevrolet C2500 3/4 Ton Pickup	**Test Article Deflections (m)**	
		Dynamic	N/A
Mass (kg)		Permanent	N/A
Curb	1893	**Vehicle Damage (Primary Impact)**	
Test inertial	2000	Exterior	
Dummy	N/A	VDS	N/A
Gross Static	2000	CDC	N/A
Impact Conditions		Interior	
Speed (km/h)	71.3	VCDI	AS0000000
Angle (deg)	20	Maximum Deformation (mm)	Negligible
Impact Severity (kJ)	45.9		

Figure 31. Summary of Results - Florida Curb End Treatment Test 71-1776-007

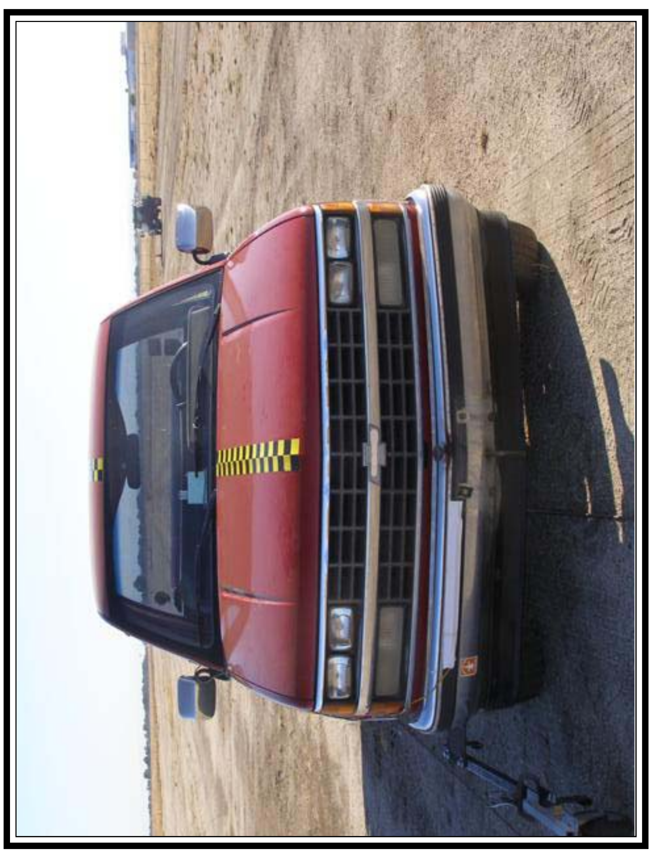


Figure 32. Pre-Test Photographs - Florida Curb End Treatment Test 71-1776-007

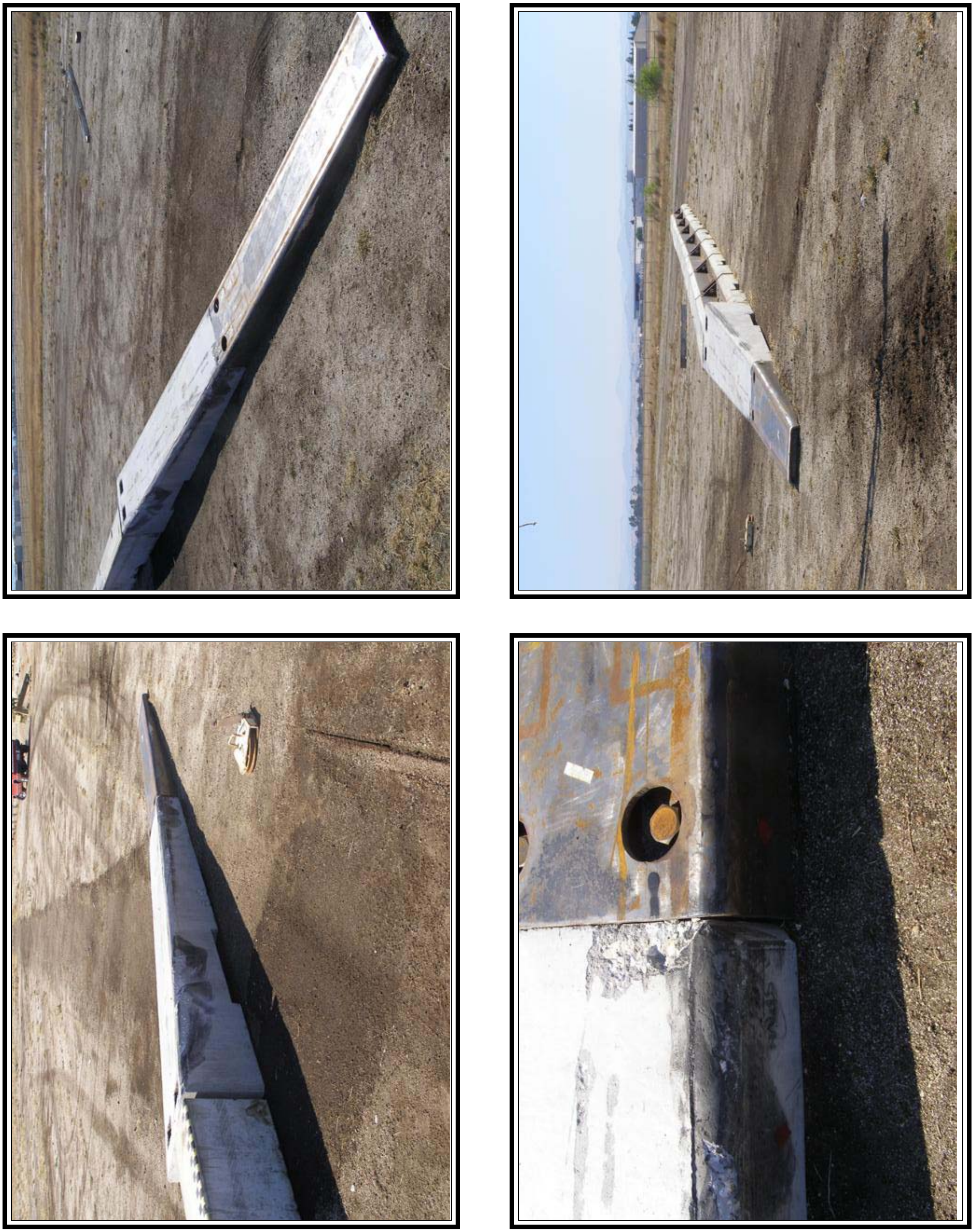


Figure 33. Test Article Damage - Florida Curb End Treatment Test 71-1776-007

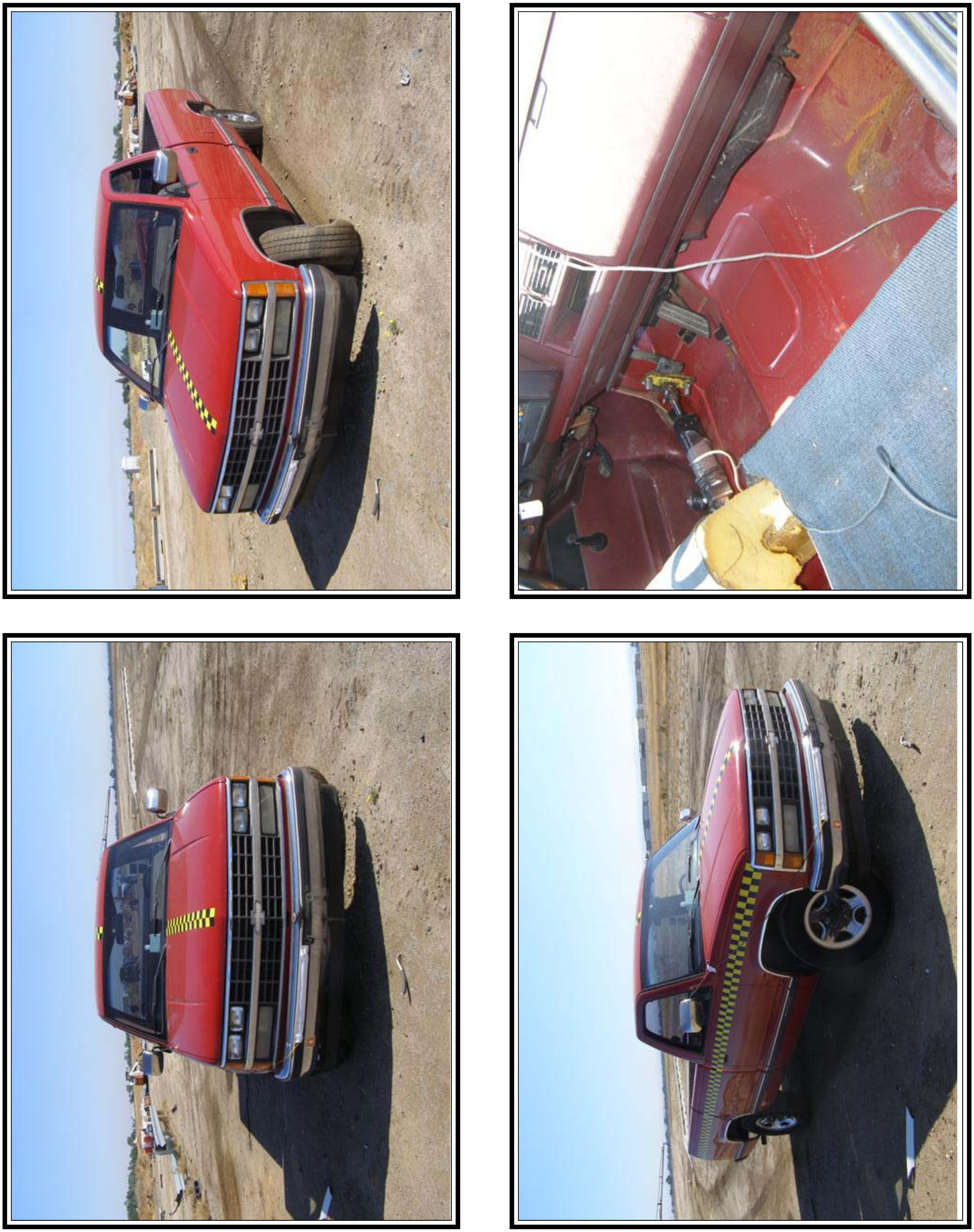


Figure 34. Vehicle Damage - Florida Curb End Treatment Test 71-1776-007

VEHICLE GEOMETRY 2000P

Test No: 71-1776-007

Date: 06/12/08

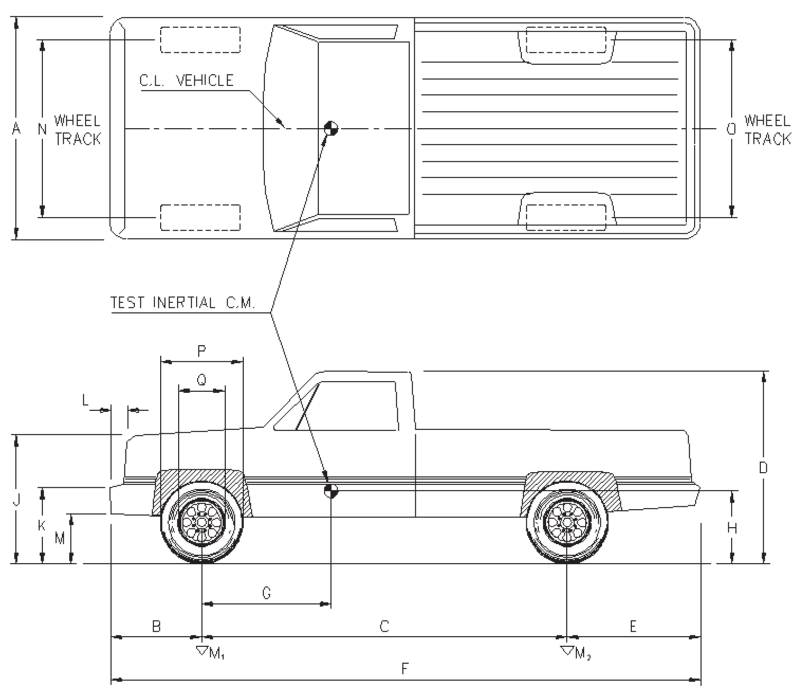
		Test Inertial Mass Distribution (kg):	
Make:	Chevrolet	**LF**	558
Model:	C2500 Pickup	**RF**	560
Year:	1988	**LR**	439
Odometer:	225201	**RR**	443

Describe any damage to vehicle prior to test:

crease over right side wheel well rear

VIN No.

1GCFC24K2JE175766



Engine Type: 8 Cylinder

Engine CID: 5.7 Liter

Transmission Type: Automatic

Optional Equipment: A/C

Dummy Data:

Type: N/A
Mass: N/A
Seat: N/A

Pretest Geometry - cm.

A	190.0	**D**	184.0	**G**	147.7	**K**	60.0	**N**	160.0	**Q**	40.7
B	86.0	**E**	130.0	**H**	75.0	**L**	10.0	**O**	161.0		
C	335.0	**F**	551.0	**J**	100.0	**M**	45.0	**P**	72.0		

Mass - kg	Curb	Test Inertial	Gross Static
M_1	1080	1118	1118
M_2	813	882	882
M_T	1893	2000	2000

Figure 35. Vehicle Geometry - Florida Curb End Treatment Test 71-1776-007

C. Assessment of Test Results

Results of the safety performance evaluation of the University of Florida Concrete Curb End Treatment are summarized in Table 1 (2 pages). The terminal was judged to have passed the NCHRP 350 structural adequacy, occupant risk, and vehicle trajectory evaluation criteria for gating end terminal Tests 30, 31, 32, 33, 34, 35, and 39.

1. Structural Adequacy

The End Treatment satisfied the NCHRP 350 structural adequacy criteria for its intended function as a gating end terminal. The test article allowed the 820C and 2000P vehicles to penetrate behind the End Treatment in a controlled fashion for both head on and angled impacts into the nose of the system. The test article also allowed the 2000P vehicle to penetrate behind the end terminal in a controlled fashion at a reverse direction angle impact at mid-length and provided redirection for a right way angled impact with the 2000P at the beginning of the length of need (BLON).

2. Occupant Risk

The occupant risk criteria were satisfied in testing the End Treatment. Theoretical occupant impact velocities in the longitudinal and lateral directions for tests involving the 820C and 2000P vehicles were well below the NCHRP 350 preferred limits. There was no test article debris to penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.

There were no deformations of the vehicle occupant compartment evident in the tests, no intrusions into the occupant compartment, and no windshield damage. All test vehicles remained upright during and after the collisions without excessive rolling, pitching, and yawing.

3. Vehicle Trajectory

The End Treatment was judged as satisfying the applicable vehicle trajectory criteria in NCHRP 350. Occupant impact velocities in the longitudinal direction for tests involving the 2000P vehicle were well below 12 m/s and ridedown accelerations were well below 20 g's. The after-collision trajectories for the 820C and 2000P vehicles subsequent to impacts on the nose of the test article were behind the test article and therefore judged as comparable to similar gating terminals currently in service.

Table 1. Curb End Treatment Test Results Evaluation Summary (1 of 2)

NCHRP 350 Evaluation Criteria	Test 71-1776-004 (NCHRP 350 Test 2-30)	Test 71-1776 005 (NCHRP 350 Test 2-31)	Test 71-1776 002 (NCHRP 350 Test 2-32)	Test 71-1776 001 (NCHRP 350 Test 2-33)	Test 71-1776 003 (NCHRP 350 Test 2-34)
******************** **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.	N/A	N/A	N/A	N/A	N/A
B. Test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.	N/A	N/A	N/A	N/A	N/A
C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	Passed	Passed	Passed	Passed	Passed
******************** **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 no be permitted.	Passed	Passed	Passed	Passed	Passed
F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	Passed	Passed	Passed	Passed	Passed
H. Occupant impact velocities (longitudinal) should satisfy the following; Preferred: 9 m/s, Maximum: 12 m/s	Passed	Passed	Passed	Passed	Passed
I. Occupant ridedown accelerations (longitudinal and lateral) should satisfy the following; Preferred: 15 g, Maximum: 20 g	Passed	Passed	Passed	Passed	Passed
******************** **Vehicle Trajectory********************					
K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Passed	Passed	Passed	Passed	Passed
L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown accelerations in the longitudinal direction should not exceed 20 g's.	N/A	N/A	N/A	N/A	N/A
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 test device.	N/A	N/A	N/A	N/A	Passed
N. Vehicle trajectory behind the test article is acceptable.	Passed	Passed	Passed	Passed	N/A

Table 1. Curb End Terminal Test Results Evaluation Summary (2 of 2)					
NCHRP 350 Evaluation Criteria	Test 71-1776-006 (NCHRP 350 Test 2-35)	Test 71-1776 007 (NCHRP 350 Test 2-39)			
******************* **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.	Passed	N/A			
B. Test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.	N/A	N/A			
C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	N/A	Passed			
******************* **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 no be permitted.	Passed	Passed			
F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	Passed	Passed			
H. Occupant impact velocities (longitudinal) should satisfy the following; Preferred: 9 m/s, Maximum: 12 m/s	N/A	N/A			
I. Occupant ridedown accelerations (longitudinal and lateral) should satisfy the following; Preferred: 15 g, Maximum: 20 g	N/A	N/A			
******************* **Vehicle Trajectory*******************					
K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Passed	Passed			
L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown accelerations in the longitudinal direction should not exceed 20 g's.	Passed	Passed			
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 test device.	Passed	Passed			
N. Vehicle trajectory behind the test article is acceptable.	N/A	Passed			

III. CONCLUSIONS AND RECOMMENDATIONS

The University of Florida Concrete Curb End Treatment was judged to have passed the NCHRP 350 structural adequacy, occupant risk, and vehicle trajectory evaluation criteria for gating end terminal Tests 30, 31, 32, 33, 34, 35, and 39. Results of the safety performance evaluation of the terminal are summarized in Section II.C. *"Assessment of Test Results"* and Table 1 of this report.

A. Test Vehicle Equipment and Guidance Methods

The test vehicle guidance method consists of a guidance cable and a reverse tow system. A wire rope guidance cable is anchored rigidly at both ends of the vehicle path. A bracket couples the front wheel of the test vehicle to the guidance cable. The guidance cable anchor closest to the test article is a low-profile steel post which forces the bracket from a wheel spindle adapter just prior to impact. The test vehicle is coupled to a tow vehicle by a tow cable. The tow cable passes through a stationary pulley mounted ahead of the impact point, through a second pulley attached to the rear of the tow vehicle, and then is anchored to the ground. Thus, as the tow vehicle pulls away from the test article the two pulleys create a 2:1 speed ratio and the test vehicle is moved at twice the tow vehicle speed toward the point of impact. Just prior to impact the tow cable is released and the vehicle is free-wheeling and unconstrained thereafter.

Each crash test vehicle is equipped with an emergency braking system which can be activated if the test needs to be aborted for safety reasons. On occasion, the braking system is applied after impact to prevent the vehicle from damaging testing equipment, or to prevent vehicle damage from secondary collisions with other fixed objects adjacent to the test area. Application of brakes is delayed as long as safely feasible, to establish the unbraked runout trajectory and velocity of the vehicle.

B. Photo Instrumentation

The key photo instrumentation parameters recommended in NCHRP 350 Table 4.1 are measured during a test. Up to eight high speed cameras may be used to record the test. Following is a description of each high speed camera:

1. Photo-Sonics, Inc. 16 mm - 1PL - (3) ea. Frame rate 10 to 500 frames per second, infinitely variable; frame rate accuracy +/-2% of frame rate setting, or +/-2 frame, whichever is greater; timing lights LED at 0.01 sec per flash.

2. Photo-Sonics, Inc. 16 mm - 1B - (1) ea. Prism rate 10 to 500 frames per second, infinitely variable; frame rate accuracy +/-2% of frame rate setting, or +/-2 frame, whichever is greater; timing lights LED at 0.01 sec per flash.

3. REDLAKE Corporation 16 mm LOCAM 50-0002 - (2) ea. Frame rate 16 to 500 frames per second, infinitely variable; frame rate accuracy +/-1% of frame rate setting, or +/-1 frame, whichever is greater; timing lights LED at 0.01 sec per flash.

4. Vision Research, Inc. Phantom v4.2 - (2) ea. High speed digital video frame rate 2100 frames per second at 512 x 512 pixel resolution up to 90,000 frames per second at 32 x 32 pixel resolution.

5. NAC Incorporated HSV-1000 - (2) ea. High speed SVHS video frame rate 1000 frames per second (half size image) or 500 frames per second (full size image); adjustable shutter speed 1/2500, 1/5000, and 1/10000 second; three-digit scene code and time indication (minutes, seconds, and milliseconds).

The before-test condition of the test article and vehicle is documented with using video, still photography, and a tape measure. High speed cameras are used to record the vehicle and test article dynamics during the crash. A minimum of two high speed film cameras are used to record side and overhead views of the impact. Overhead cameras typically provide fields of view perpendicular to the ground and directly over the impact point. Side view cameras typically provide fields of view perpendicular and/or parallel to the test article centerline. Other high speed film cameras may be used to record additional fields of view of the test article and/or the vehicle interior when windshield damage and occupant compartment deformation and intrusion is of concern. High speed and real time video cameras may also used to record additional and typically narrow close up fields of view. The post test phase is again documented with video, photography, and a tape measure. Any significant debris is located and photographed. Film data is analyzed on a NAC Model DF-16C analysis projector capable of advancing 16 mm film data one frame at a time. High speed digital video is analyzed with Vision Research Phantom Camera Control software and high speed SVHS video is analyzed on a NAC 1000 FPS video analyzer capable of advancing the video data one frame at a time.

C. Electronic Instrumentation and Data Plots

The key test parameters recommended in NCHRP 350 Table 4.1 are measured during testing. Except as noted in NCHRP 350, the electronic instrument specifications in the publication SAE J211 OCT88 "Instrumentation for Impact Test" are used. With regard to NCHRP 350 Sections 4.3.2 and A5.3, the following exceptions are made to the electronic instrumentation: (1) the Simpson's Rule numerical method is used to integrate the digitized accelerometer data, (2) plots of acceleration versus time are filtered to 300 Hz.

E-TECH utilizes primary and backup data acquisition systems to guard against data loss. Each system collects x, y, and z accelerations as well as roll, pitch, yaw, and speed. Each system employs a triaxial set of Entran Model EGCS-D1S-100 accelerometers and a triaxial set of Systron Donner GyroChip II QRS14-00500-103 roll, pitch and yaw rate transducers arranged on a common lightweight steel block and mounted on major structural elements of the vehicle. A Channel Amplitude Class (CAC) of 140 g's is selected so as to maximize the accuracy of the expected results, without exposing the accelerometers to undue risk of damage.

The primary accelerometer block is placed within +/- 5 cm of the center of vehicle mass, as measured in the x-y plane with positive directions corresponding to the location and sign conventions given in NCHRP 350. Typically the two most probable causes of data loss are instrumentation failure and spurious events such as floorboard buckle. In order to take safeguards against both modes of data loss, the backup set of accelerometers is located approximately 1200 mm rearward of the c.g. along the x-axis of the vehicle. As a consequence backup data does not technically meet the "within +/- 5 cm of the vehicle c.g." requirements of NCHRP 350. However, longitudinal occupant risk measurements which are typically the most critical are unaffected by the rearward mounting.

The unfiltered output signals from the accelerometers and rate transducers, along with optical switch speed trap information, are filtered to 301 Hz and recorded in the vehicle using fully redundant GMH Engineering DataBrick onboard data acquisition systems, equipped with a 12-bit analog to digital converters digitizing at a rate of 4042 Hz. The recorded digital signals are subsequently manipulated using DSP Development Corporation's DADiSP worksheet signal analysis software running special processing worksheets that have been validated via cooperation in interlaboratory comparison programs.

E-TECH's data acquisition and analysis procedures specify that under normal circumstances only readings from the primary data acquisition system will be reported in NCHRP 350 certification test reports. However, in the event of partial or complete primary data loss, values from each available data channel will subsequently be reported in all correspondence, including NCHRP 350 Certification reports.

The standardized occupant impact velocity and ridedown acceleration calculation procedures, recommended in NCHRP 350, Section A5.3 are followed in the data acquisition and analysis procedures. The vehicular accelerations in the x and y directions are numerically integrated to determine the theoretical occupant impact velocities in the x and y directions.

The theoretical occupant impact velocity occurs at the time (flail space time) when the theoretical occupant has traveled either 0.6 m forward, or 0.3 m lateral, whichever calculated time is smaller. The flail space time is determined by incremental integration of the vehicular acceleration. The acceleration in the x direction is integrated twice with respect to time to find the flail space time at which the double integration equals 0.6 m. Acceleration in the y direction is integrated twice with respect to time to find the flail space time at which the double integration equals 0.3 m. Finally, a 10 ms moving average of the x and y vehicular accelerations is taken, and the ridedown accelerations are reported as the highest 10 ms average vehicular accelerations in the x and y directions, subsequent to the flail space time.

Although not required by NCHRP 350, testing agencies are encouraged to calculate and report the Theoretical Head Impact Velocity (THIV), Post-Impact Head Deceleration (PHD), and the Acceleration Severity Index (ASI). These measures have been adopted by the European Committee for Standardization (CEN) as measures of occupant risks and are calculated according to the procedures contained in EN 1317-1 Sections 6 and 7.

Two reference frames are used in the THIV calculation, the first is a vehicular reference and the second is a ground reference frame. The vehicle and theoretical occupant head motion are computed using the x and y accelerations and yaw rate at or near the vehicle center of gravity. The yaw angle is computed by integration of the yaw rate and the vehicular velocity and position are computed from the components of vehicular acceleration in the ground reference. The time of flight of the theoretical head is the time of impact on one of the three notional impact surfaces inside the vehicle. The distances between these surfaces and the original head position are the 0.6 m forward and 0.3 m lateral flail space distances. The THIV is the relative velocity of the occupant at the time of impact, the square root of the sum of the squares of the lateral and longitudinal head velocities at this time.

The PHD is the maximum value of the vehicle accelerations, occurring after the time of the collision of the theoretical head. The PHD is the maximum of the square root of the sum of the squares of the lateral and longitudinal 10 ms moving average accelerations.

The ASI is computed by taking a 50 ms moving average of the x, y, and z vehicular accelerations and then normalizing the values by dividing by limit accelerations (12, 9, and 10 g's, respectively). These values are then squared and summed, and the ASI is computed as a function of time as the square root of this sum.

Figure C-1 through C-24 contain angular displacement, longitudinal, lateral, and vertical g-traces, THIV, PHD, and ASI plots for Vorteq Trailer TMA Tests 01-4232-003, 001, 002, and 004.

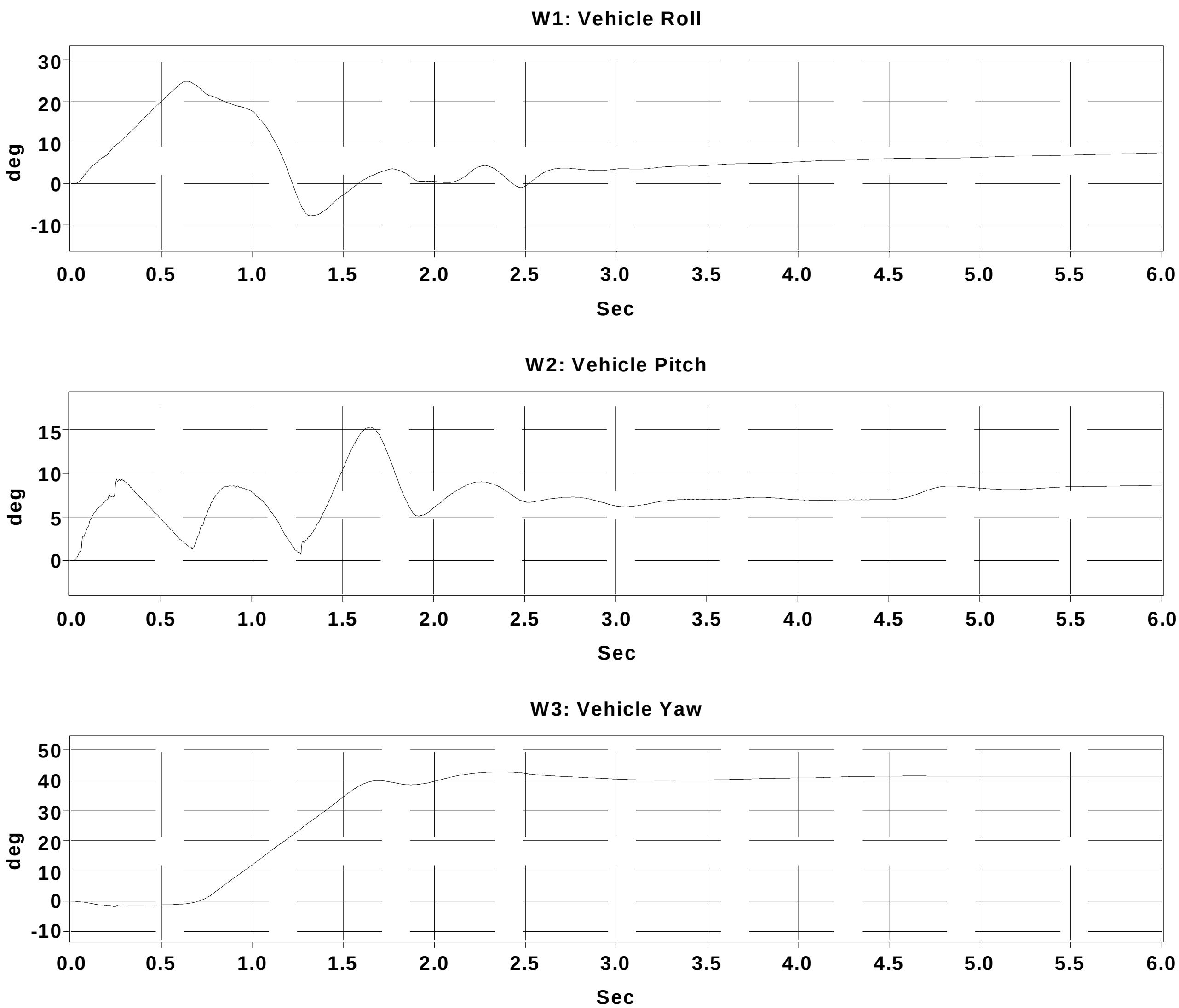


Figure C-1. Vehicular Angular Displacements - Test 71-1776-004

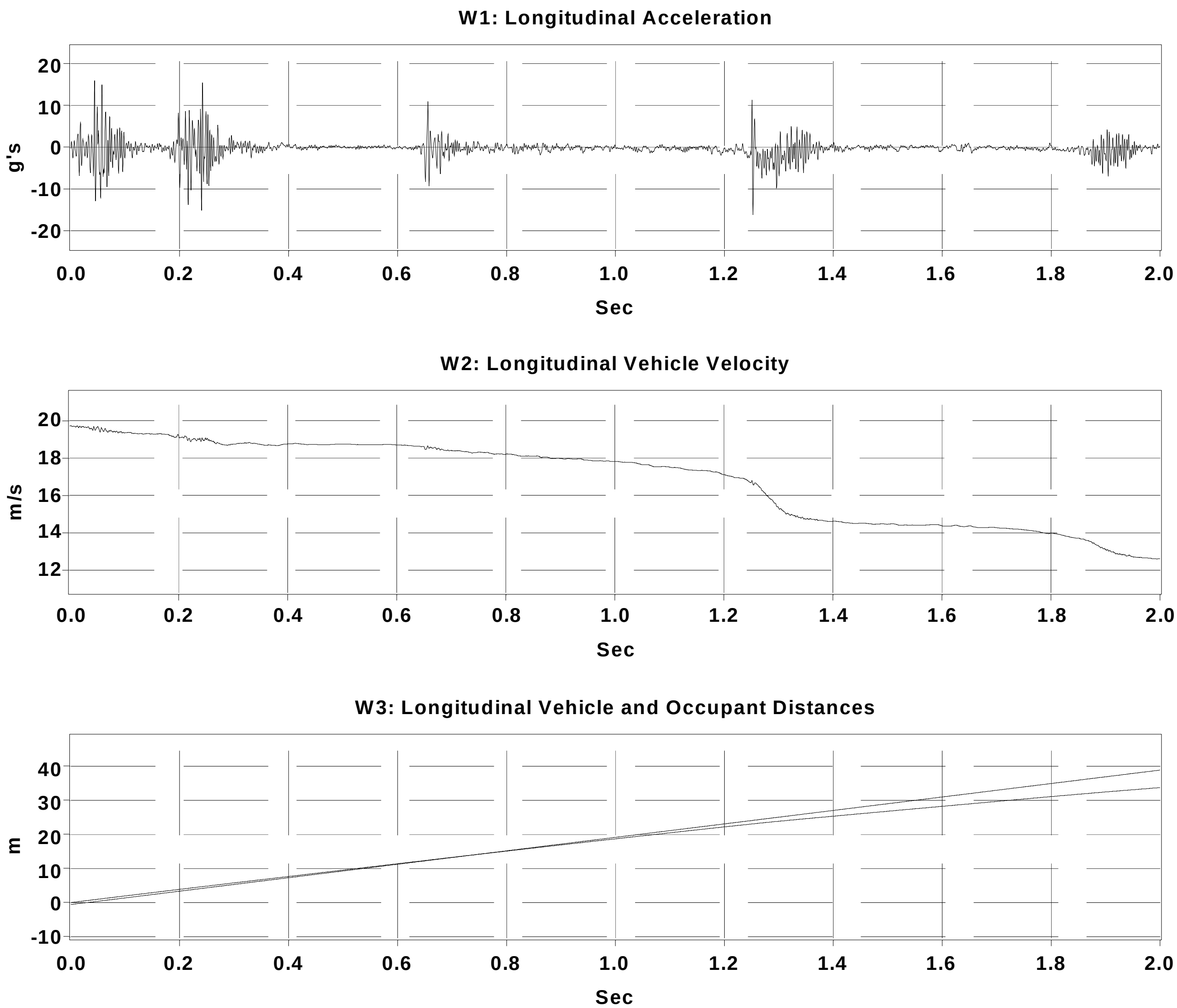


Figure C-2. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-004

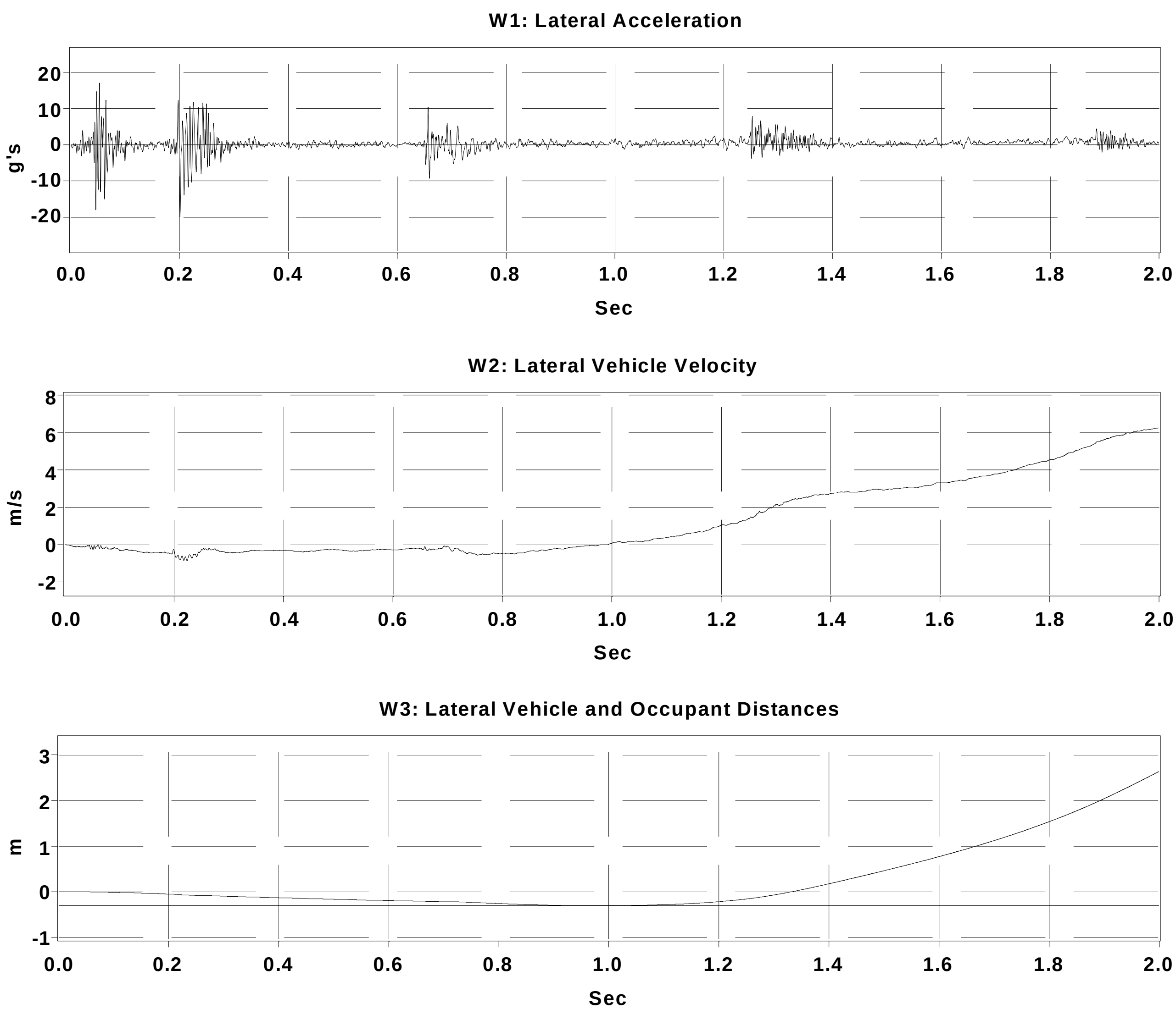


Figure C-3. Lateral g-Trace/Occupant Kinematics - Test 71-1776-004

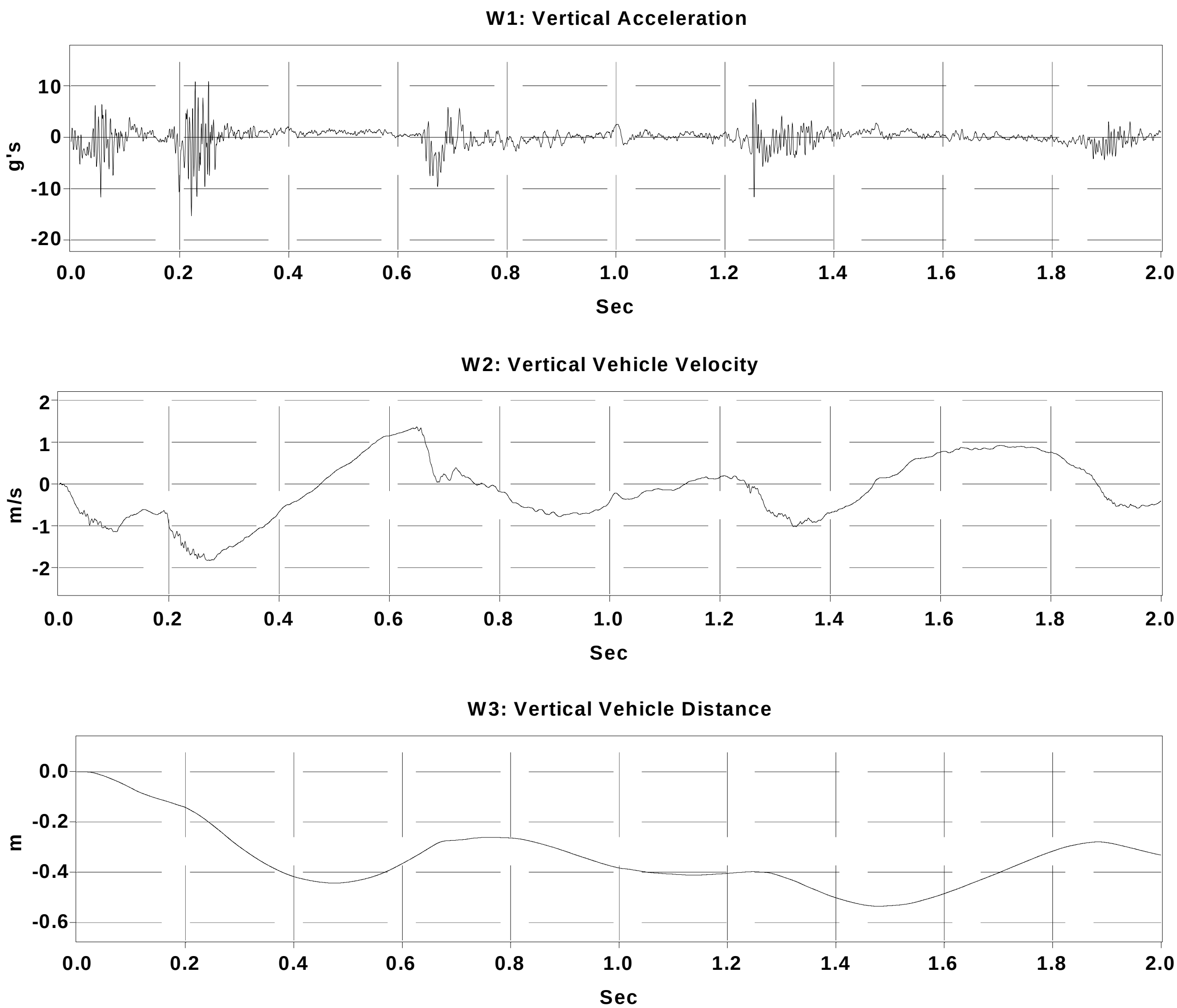


Figure C-4. Vertical g-Trace/Occupant Kinematics - Test 71-1776-004

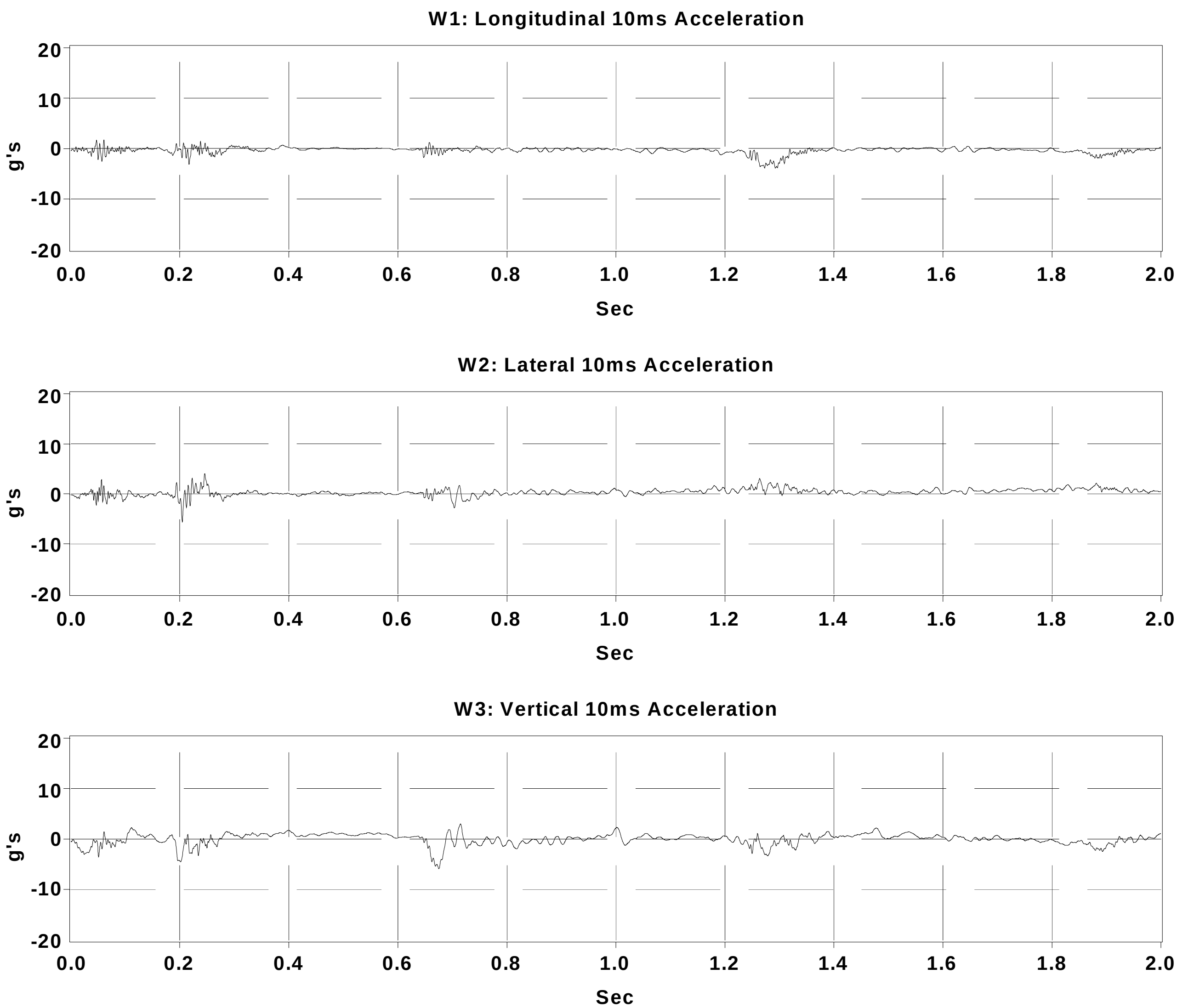


Figure C-5. 10 ms Average Vehicle Accelerations - Test 71-1776-004

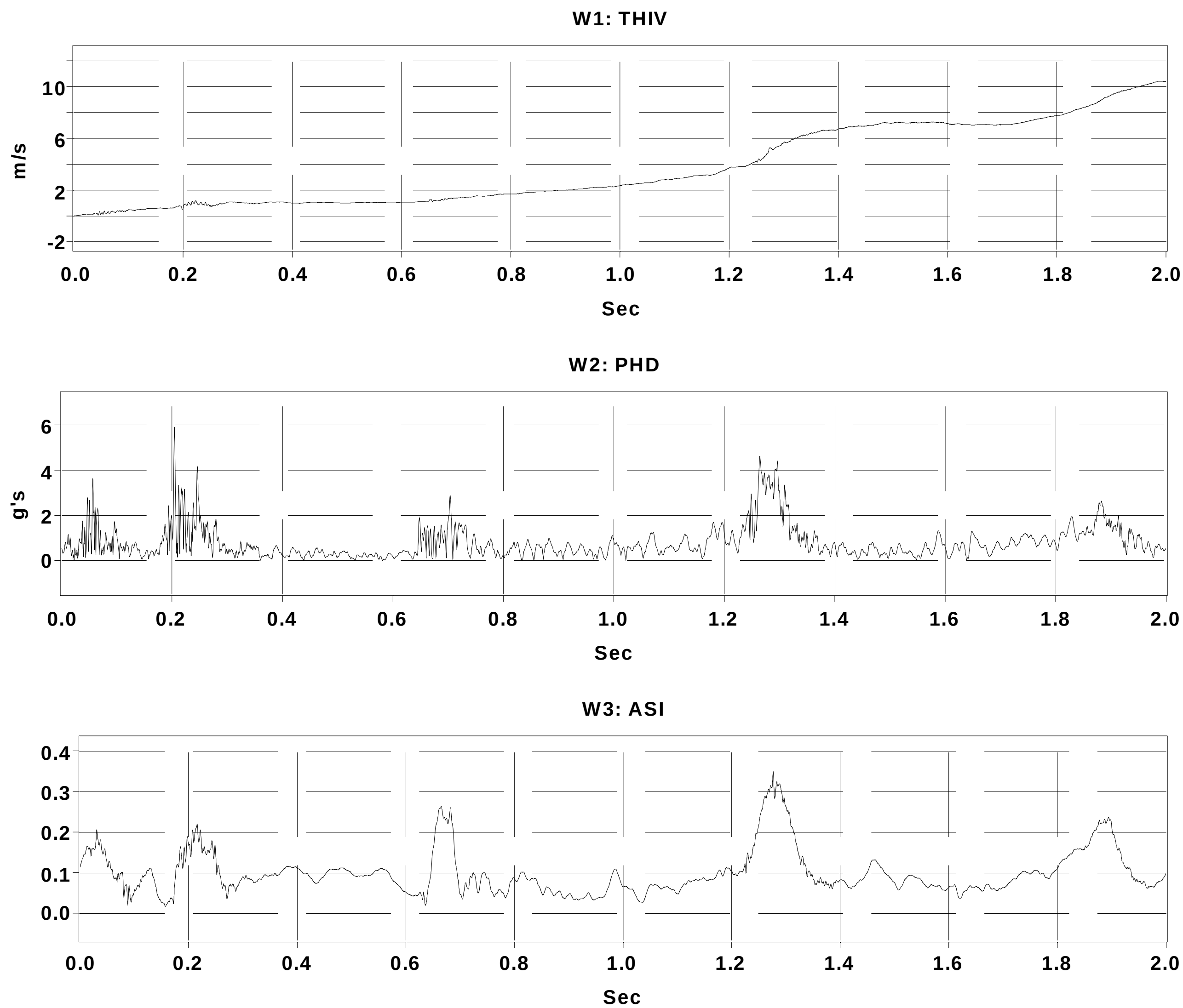


Figure C-6. THIV, PHD, and ASI - Test 71-1776-004

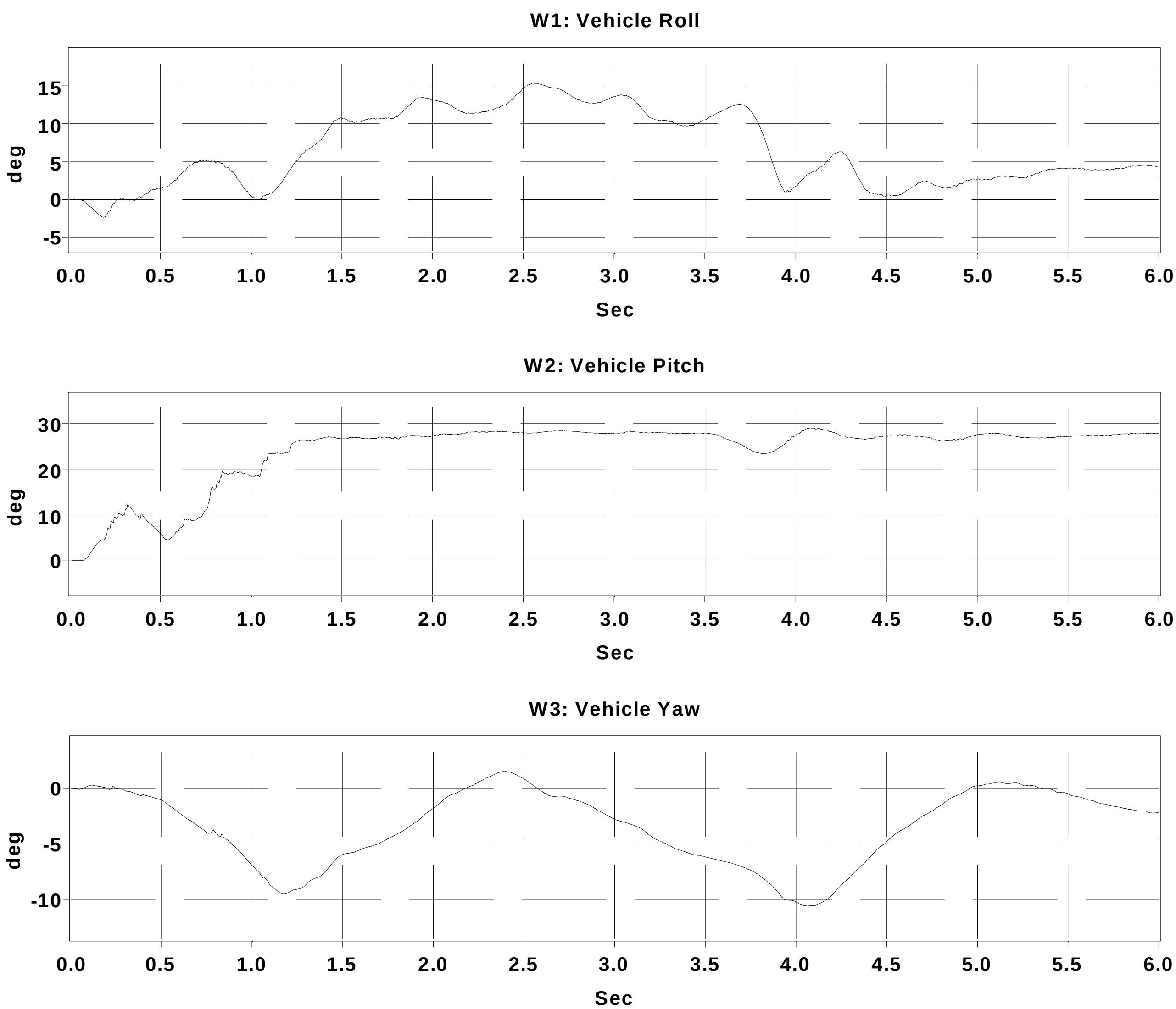


Figure C-7. Vehicular Angular Displacements - Test 71-1776-005

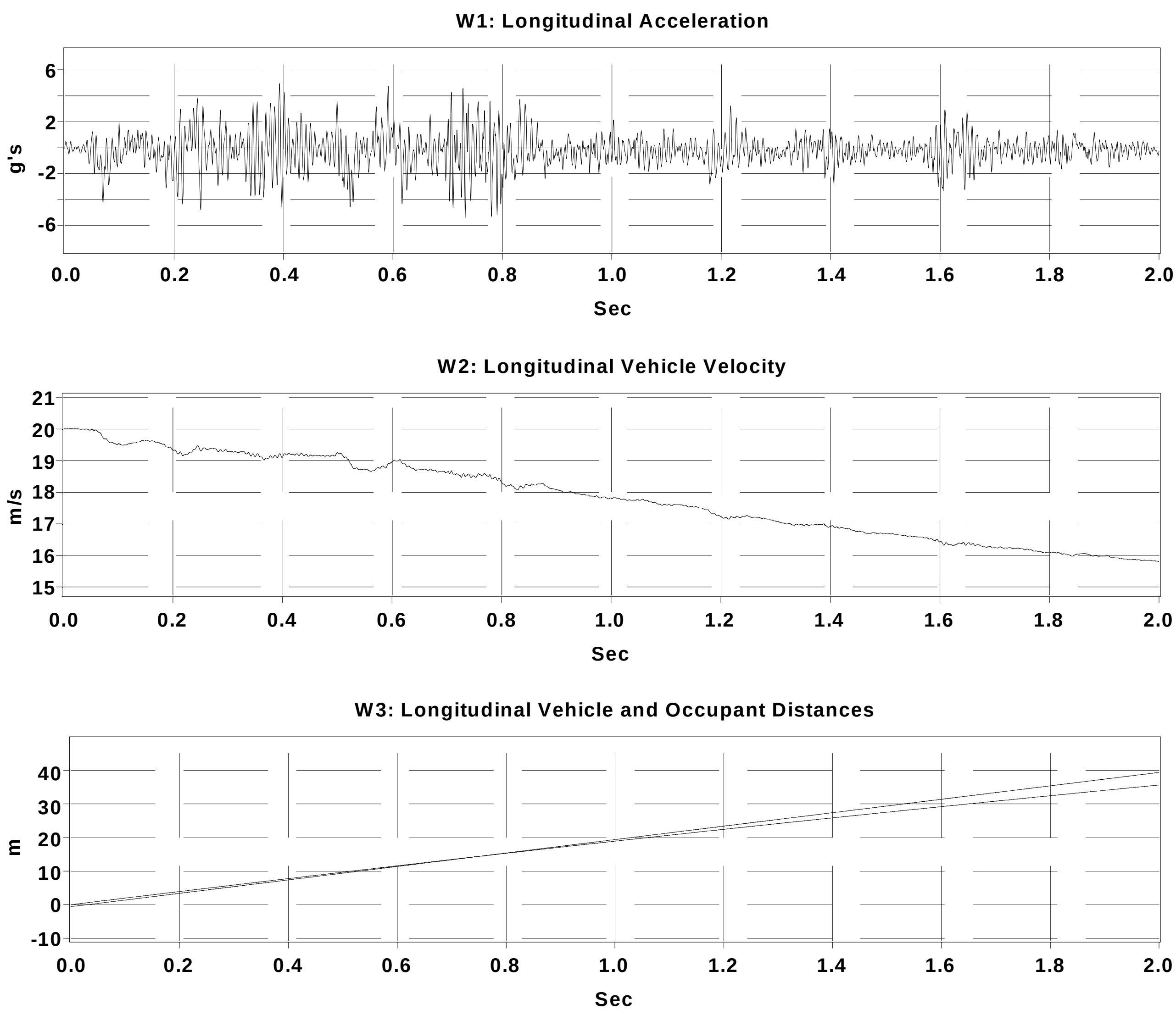


Figure C-8. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-005

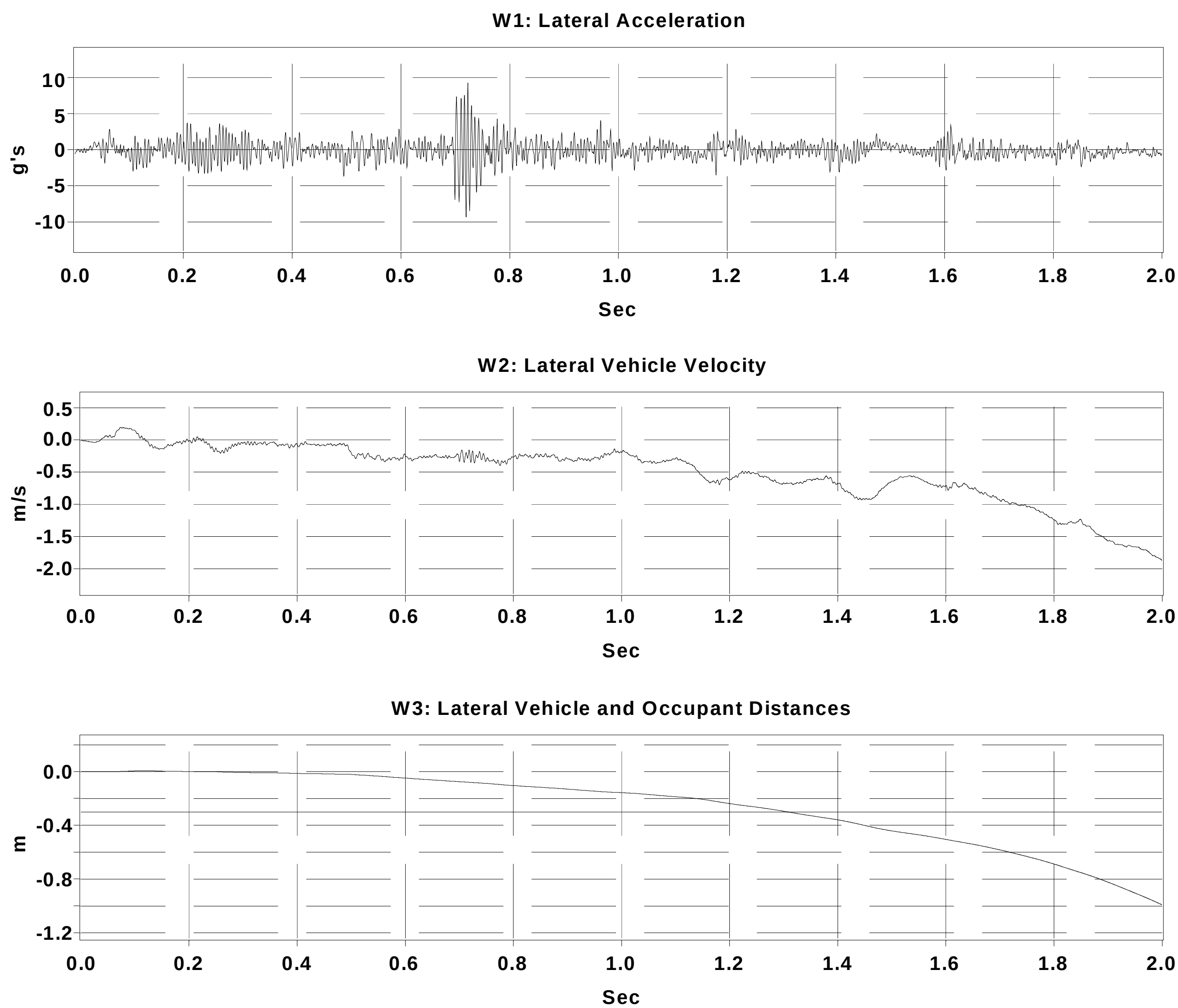


Figure C-9. Lateral g-Trace/Occupant Kinematics - Test 71-1776-005

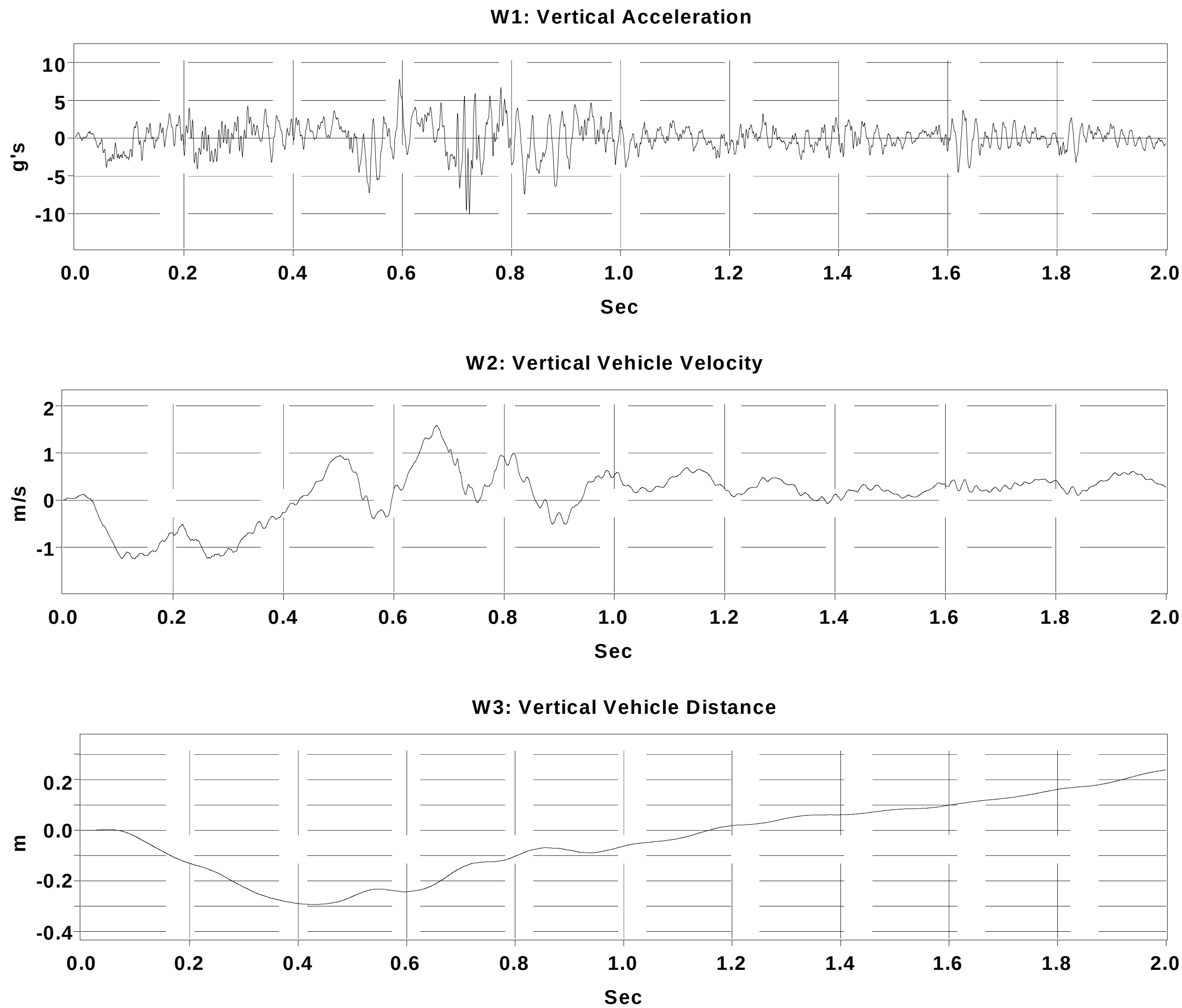


Figure C-10. Vertical g-Trace/Occupant Kinematics - Test 71-1776-005

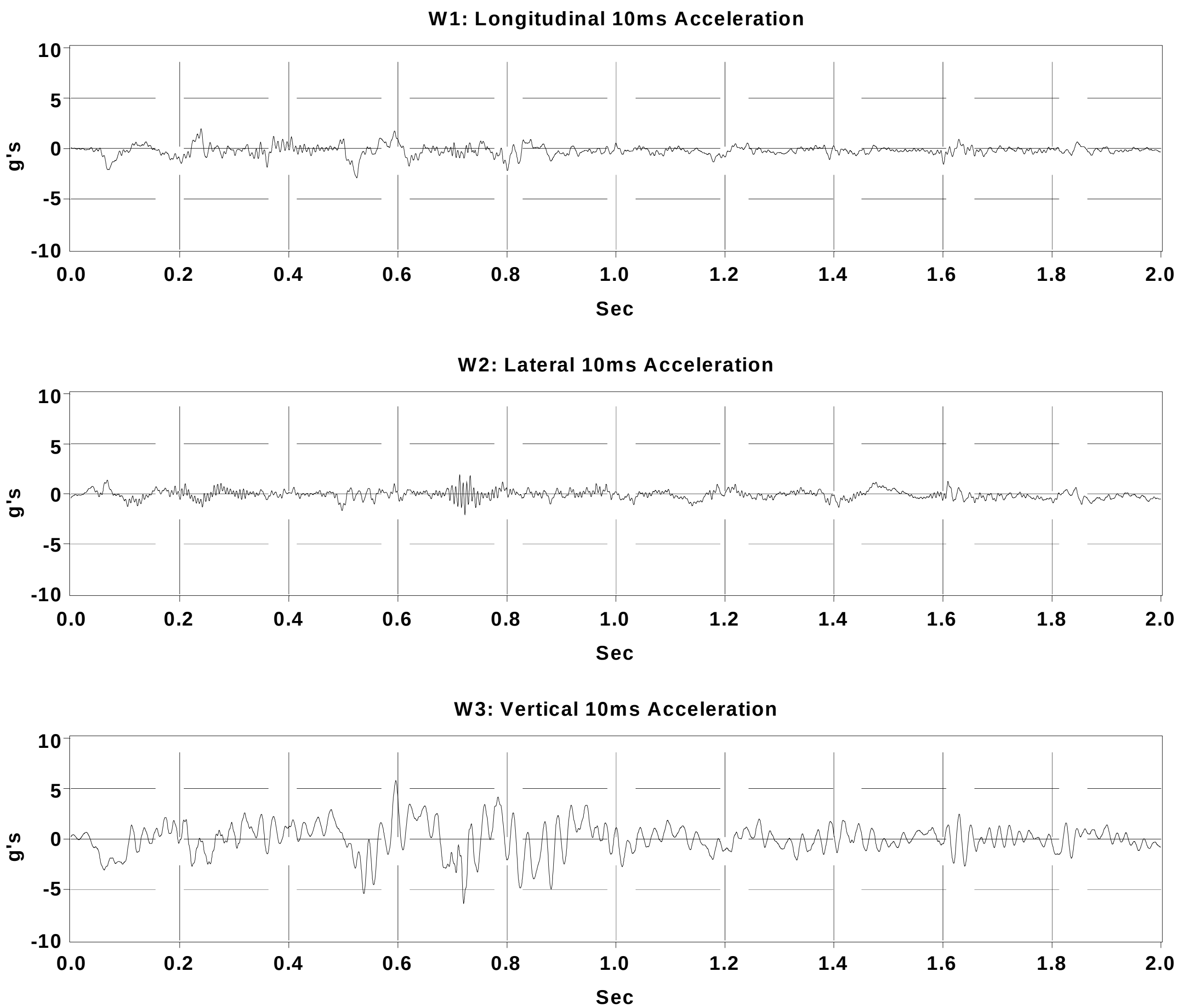


Figure C-11. 10 ms Average Vehicle Accelerations - Test 71-1776-005

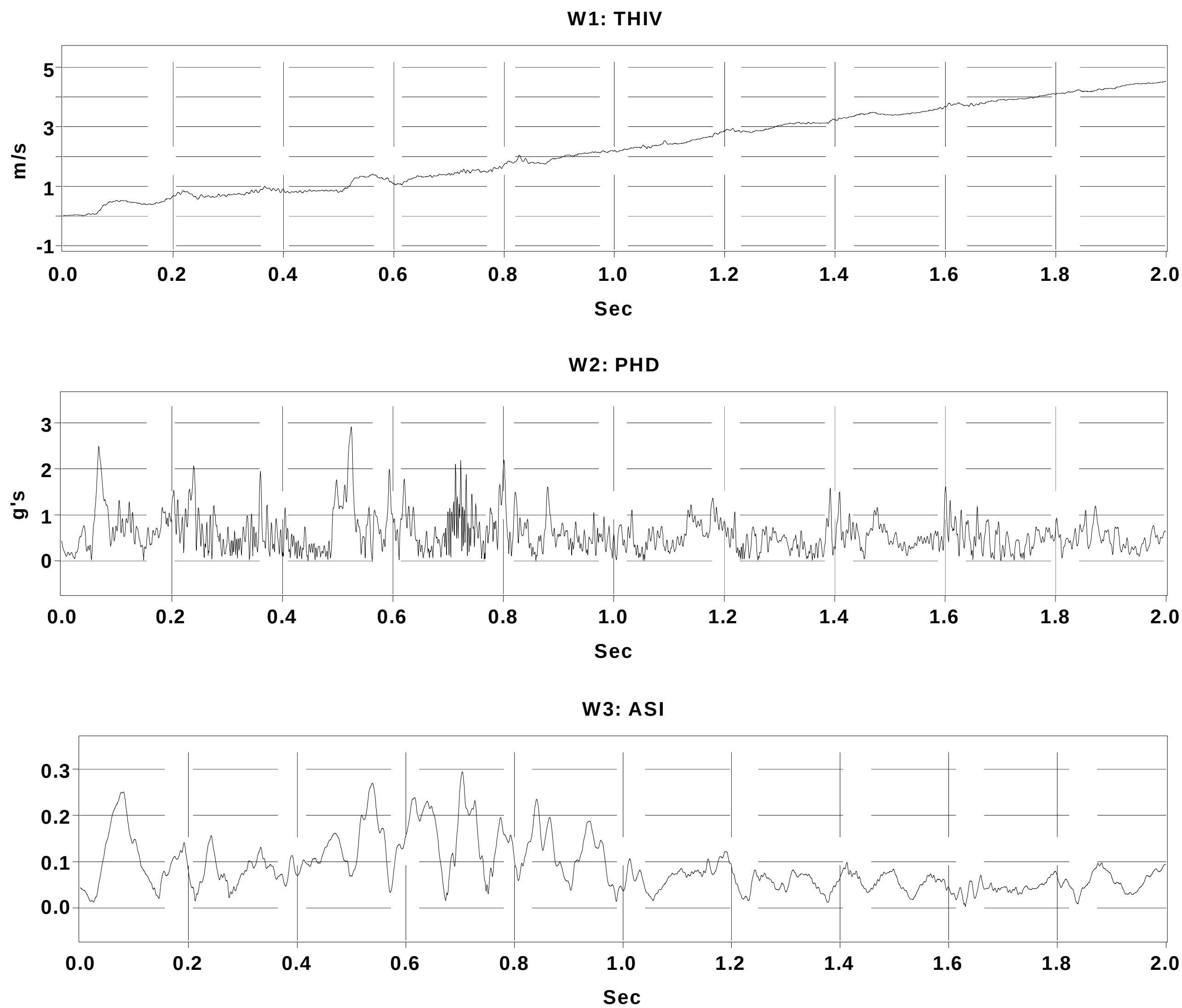


Figure C-12. THIV, PHD, and ASI - Test 71-1776-005

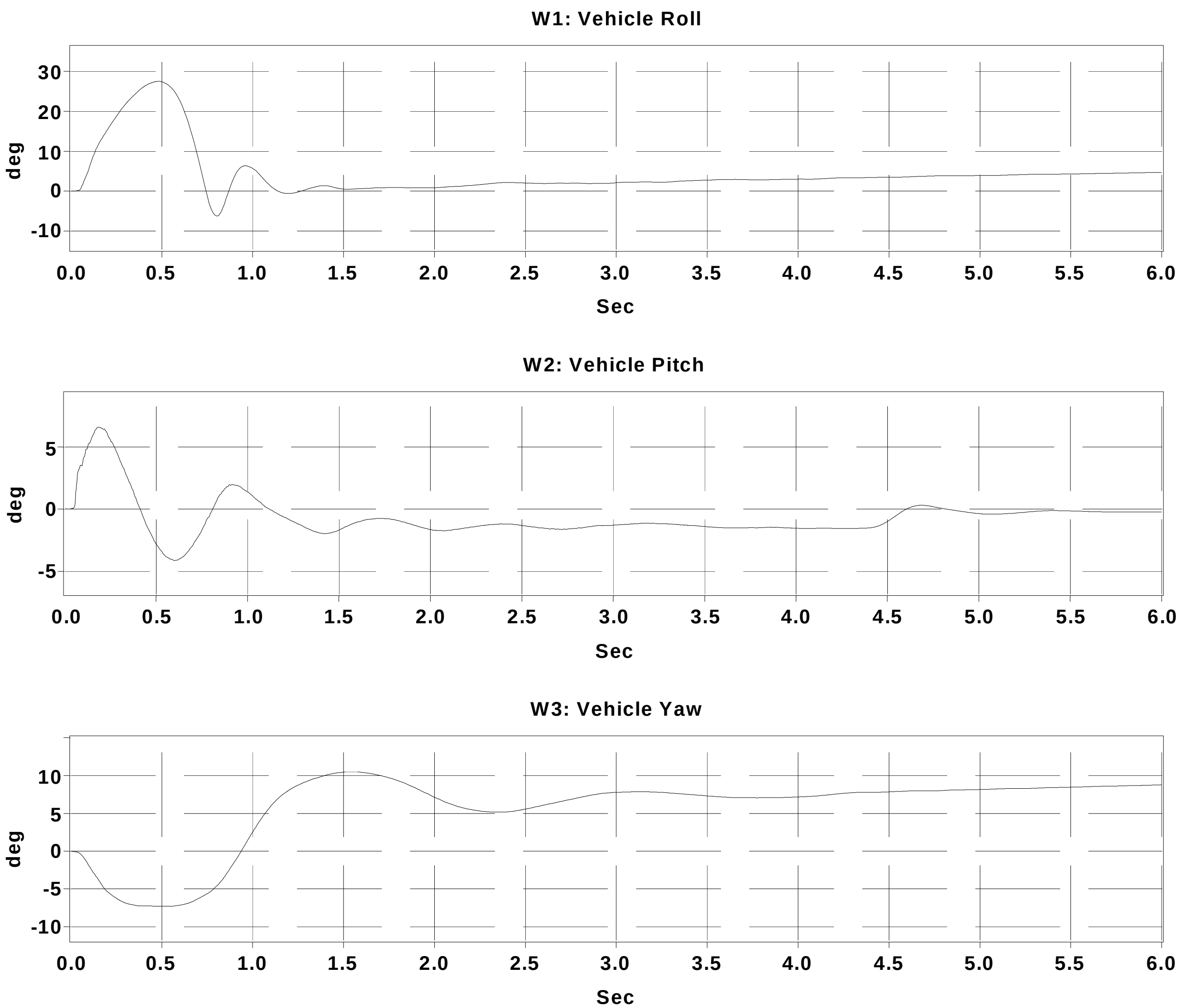
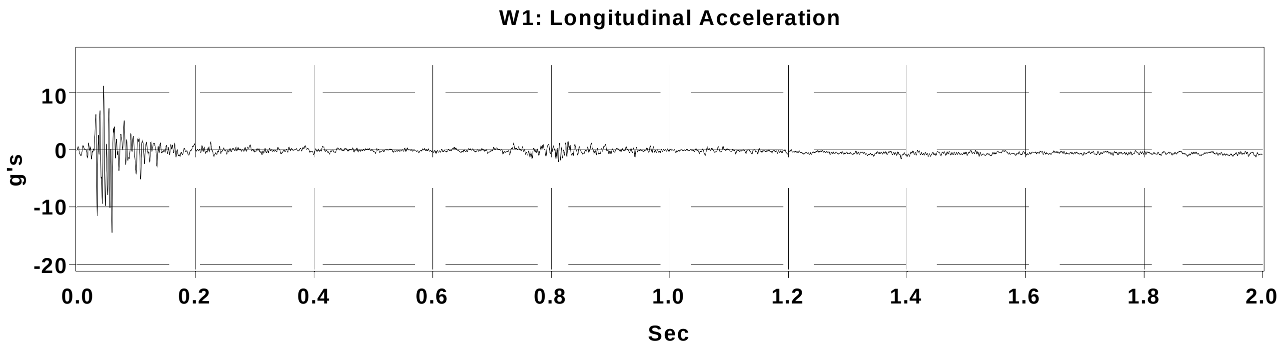
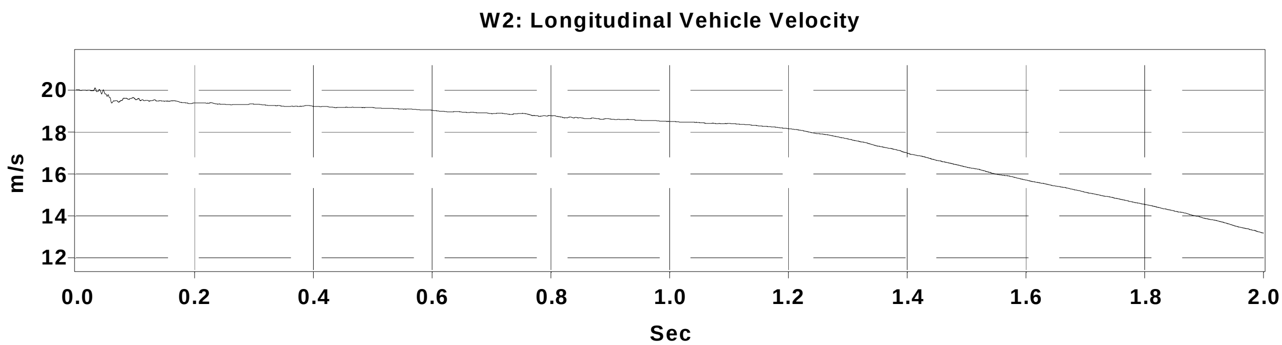


Figure C-13. Vehicular Angular Displacements - Test 71-1776-002





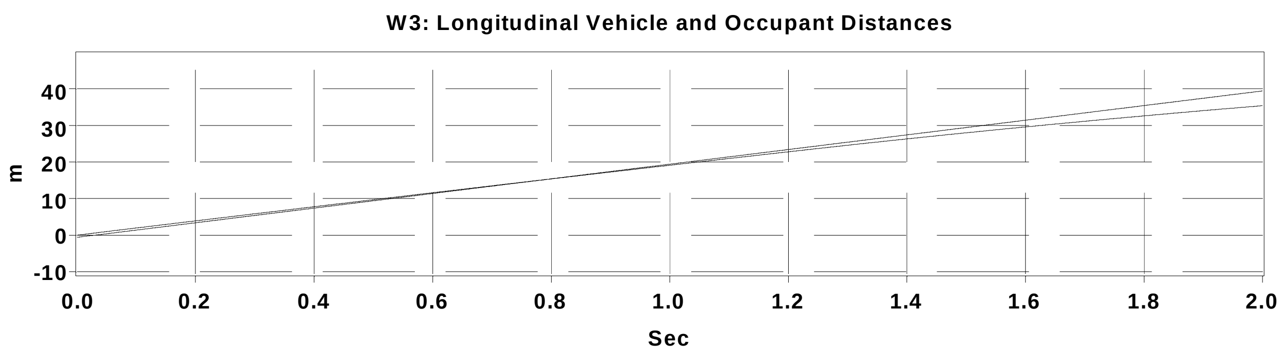


Figure C-14. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-002

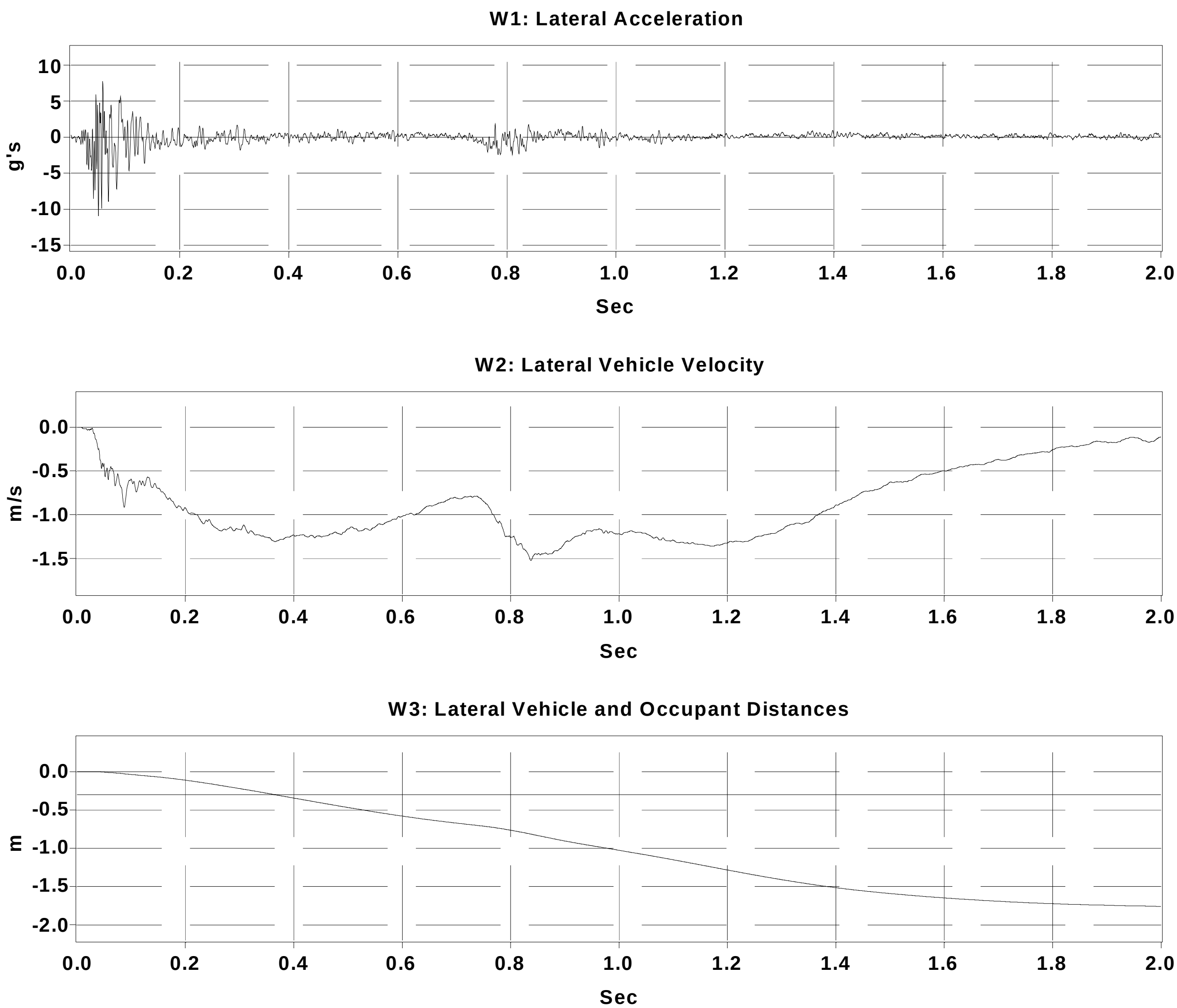


Figure C-15. Lateral g-Trace/Occupant Kinematics - Test 71-1776-002

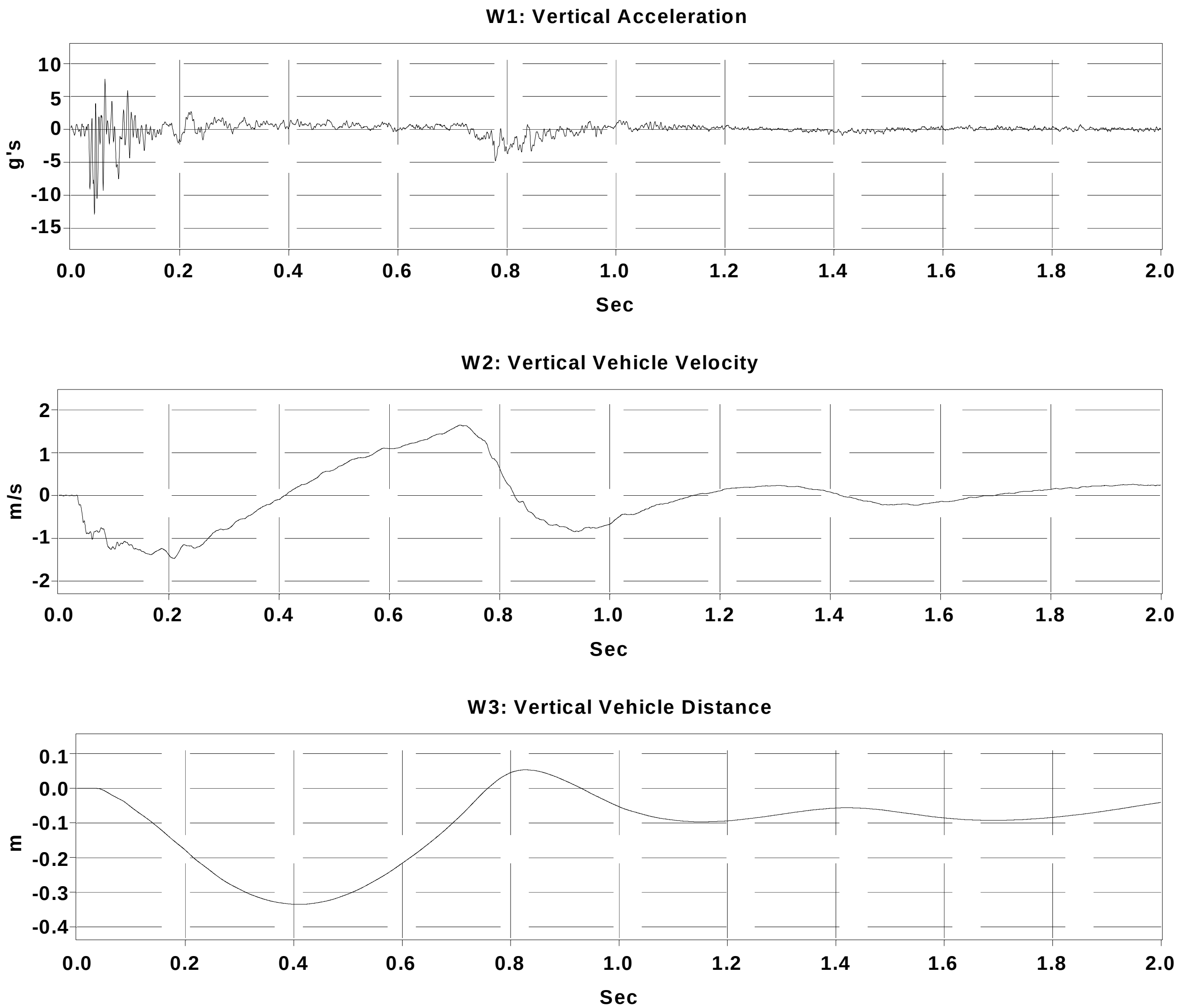


Figure C-16. Vertical g-Trace/Occupant Kinematics - Test 71-1776-002

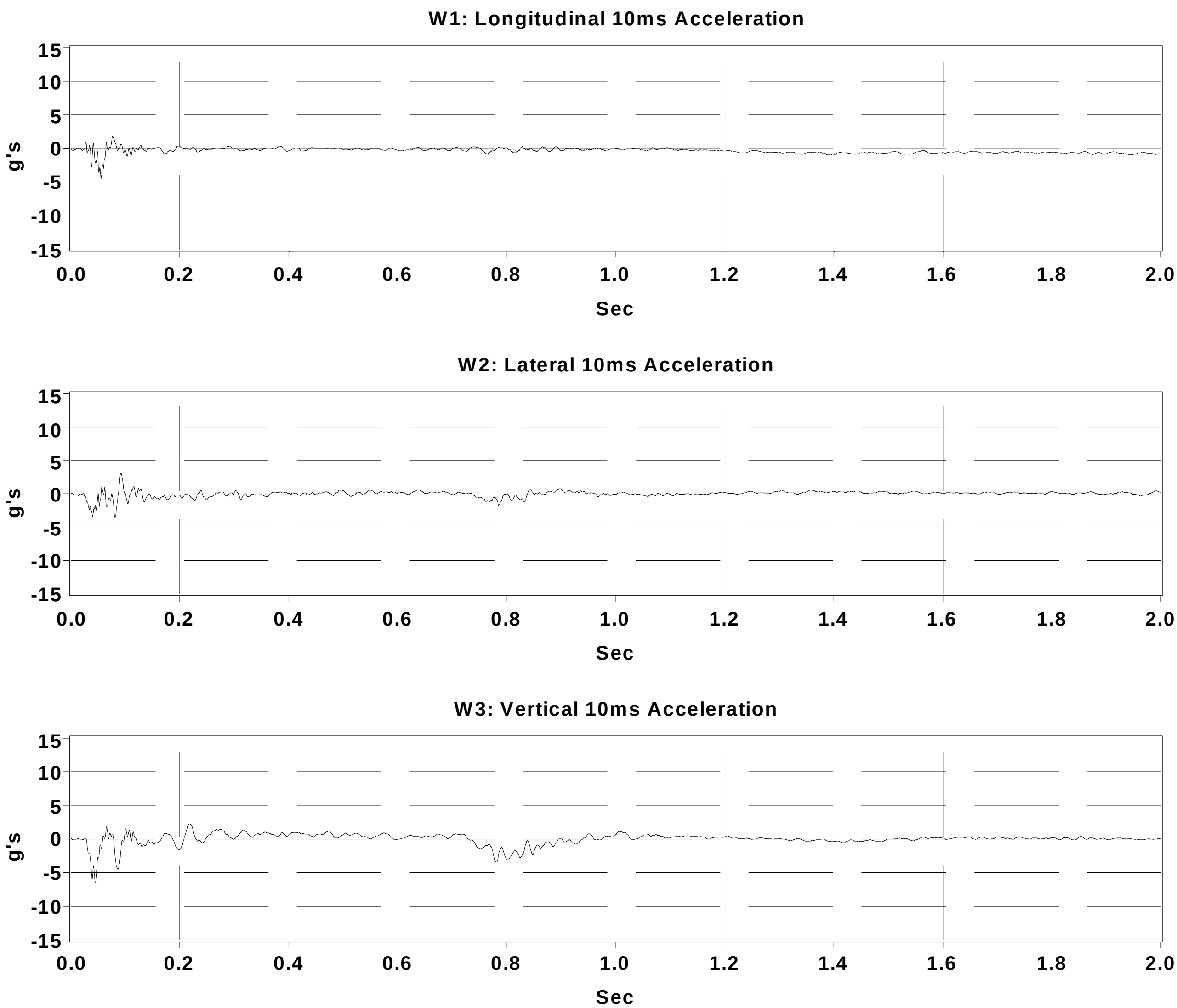


Figure C-17. 10 ms Average Vehicle Accelerations - Test 71-1776-002

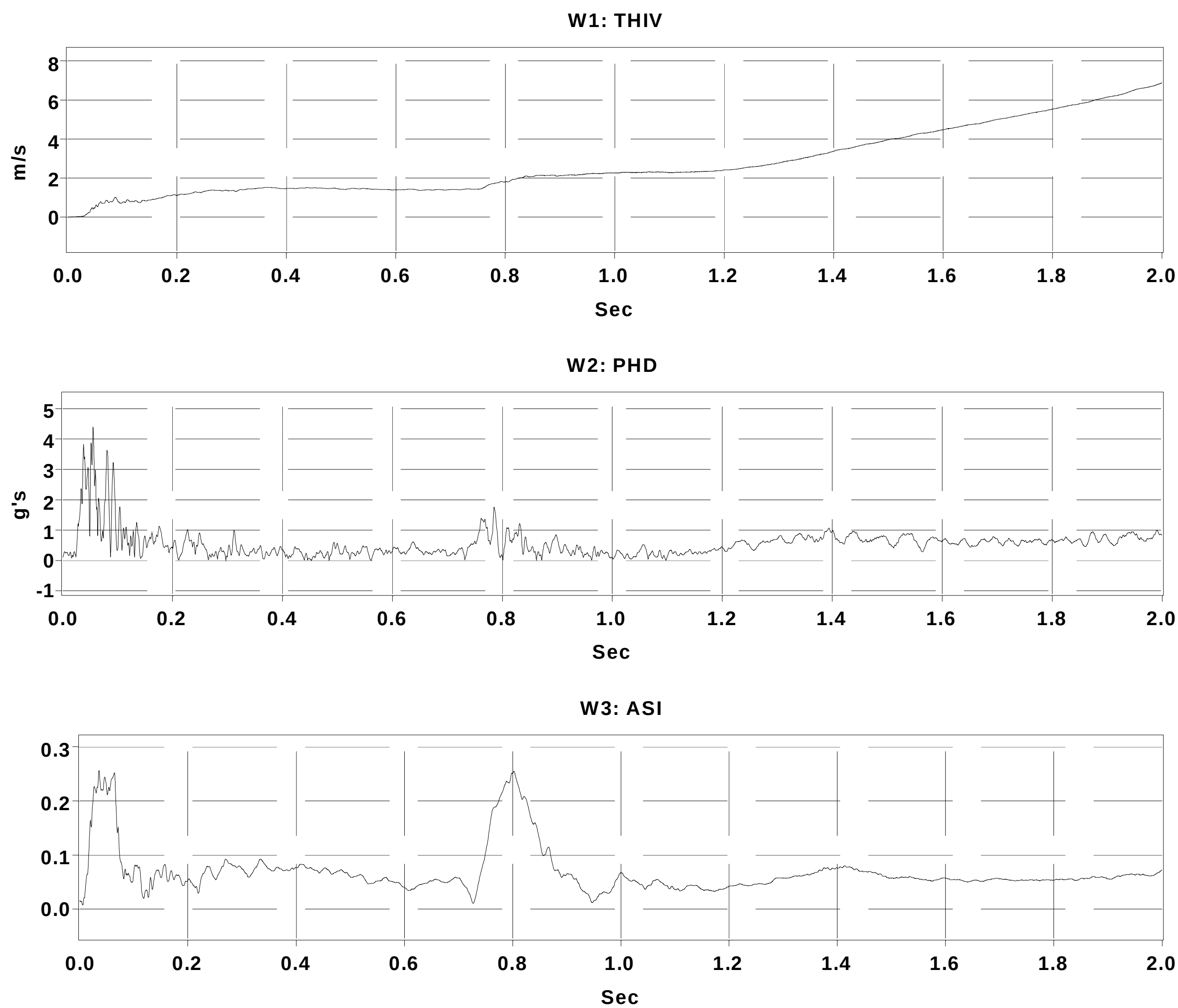
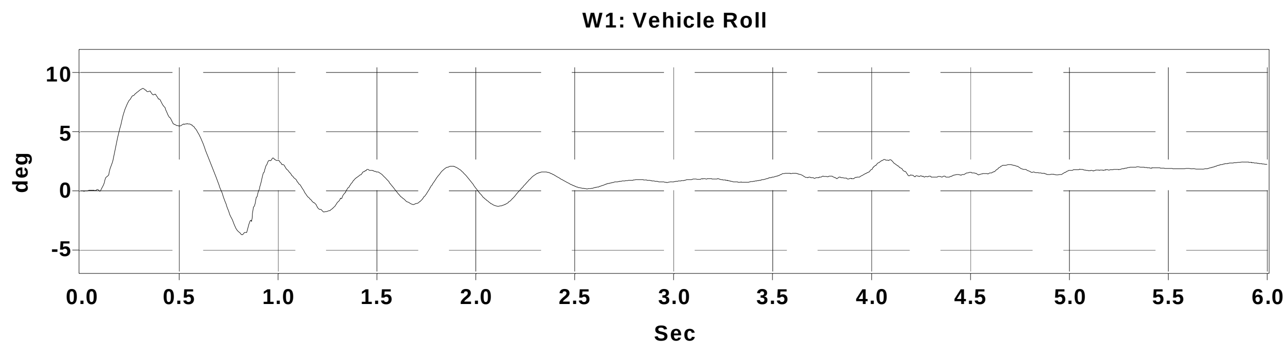
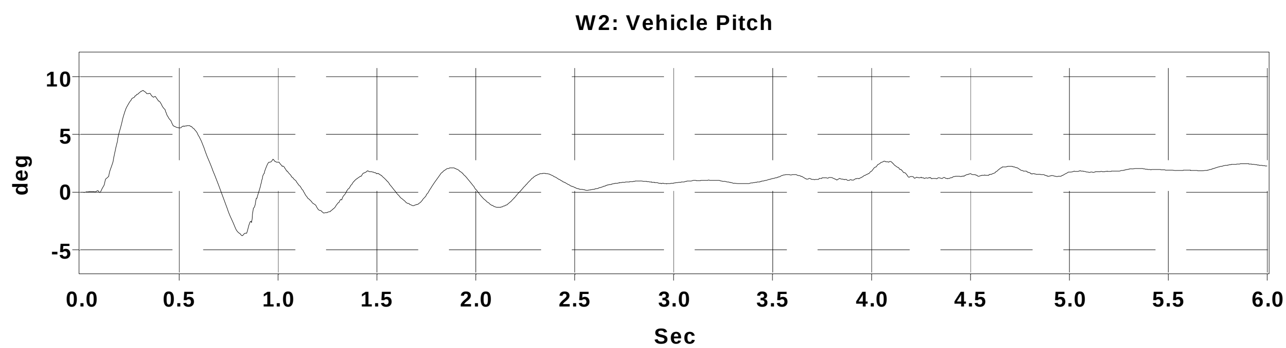


Figure C-18. THIV, PHD, and ASI - Test 71-1776-002





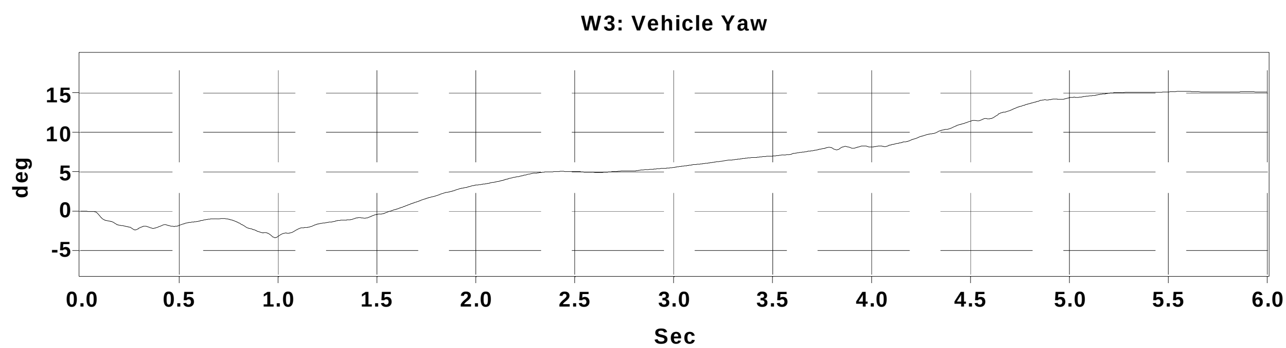


Figure C-19. Vehicular Angular Displacements - Test 71-1776-001

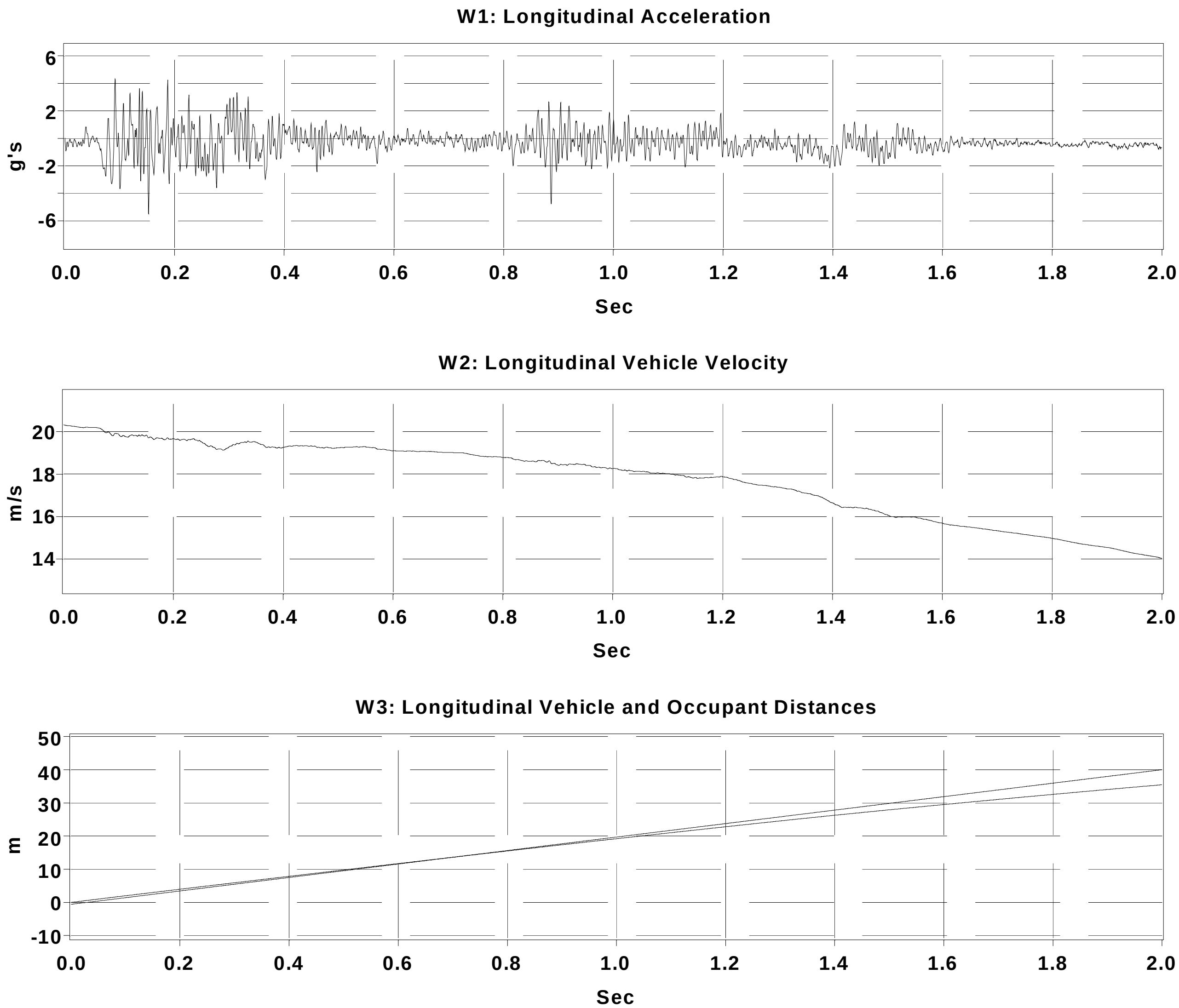


Figure C-20. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-001

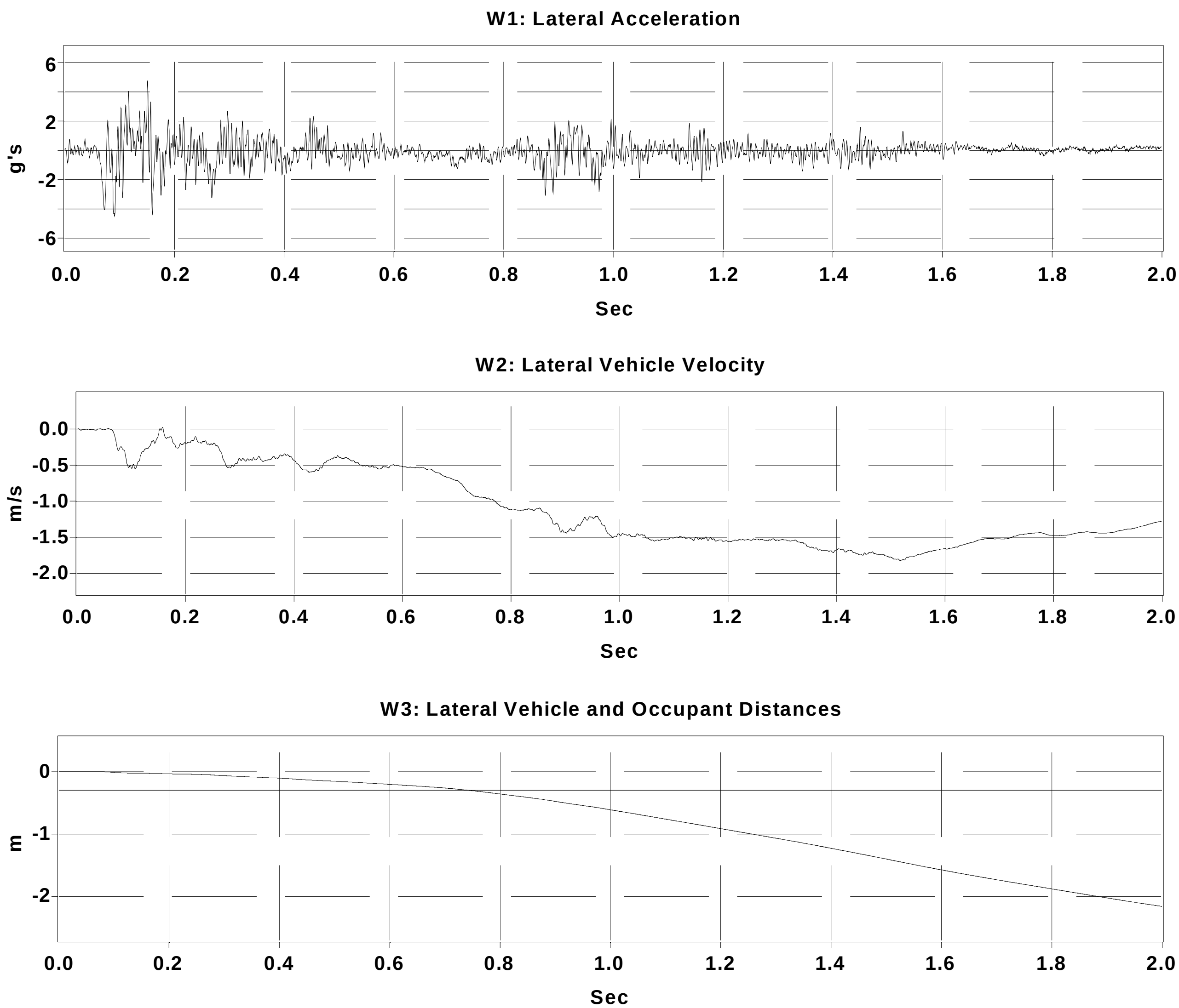


Figure C-21. Lateral g-Trace/Occupant Kinematics - Test 71-1776-001

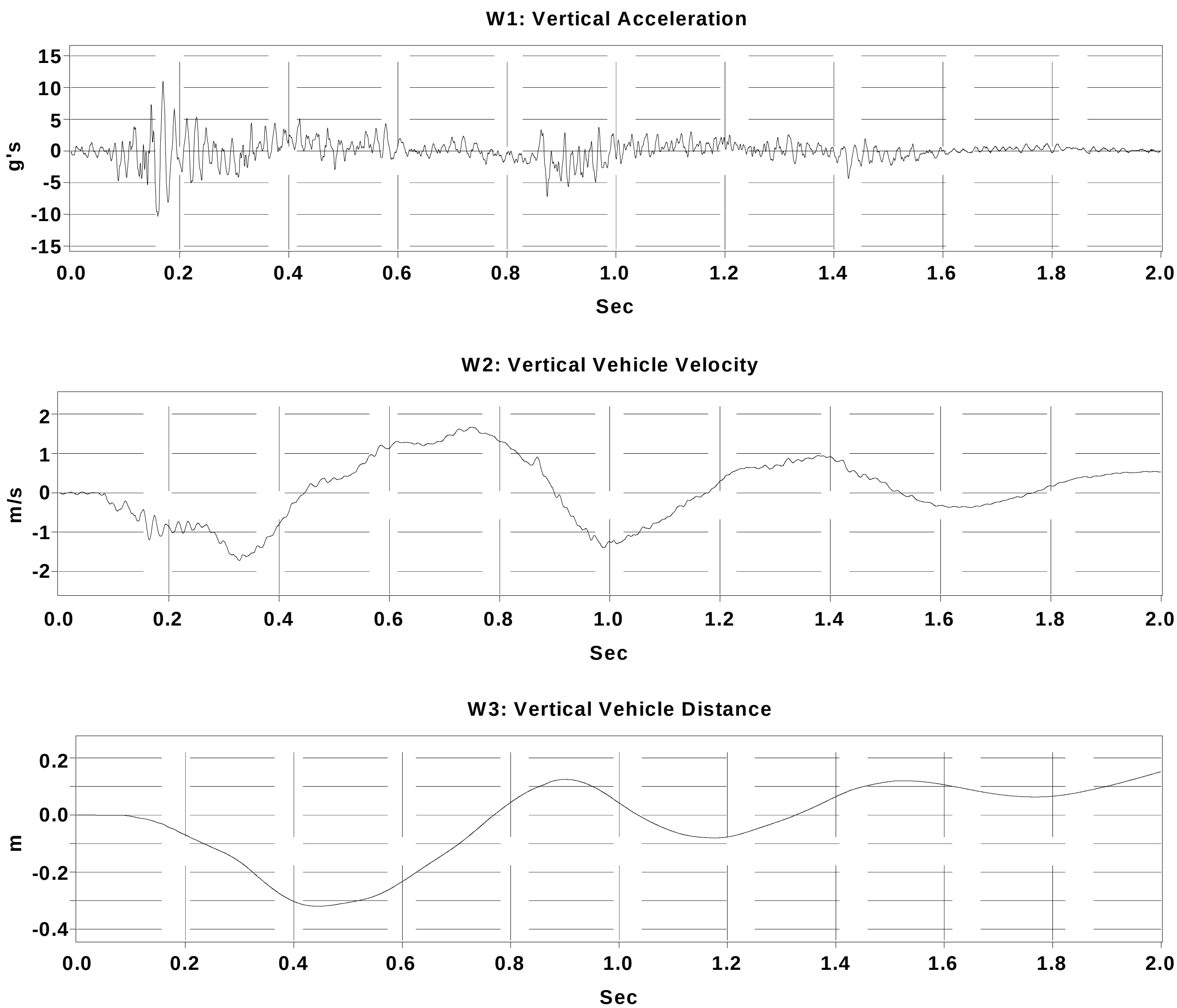
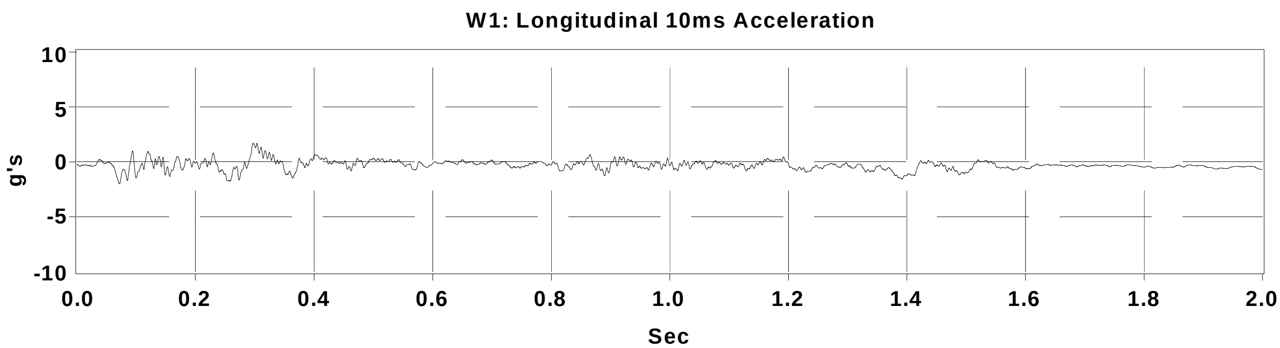
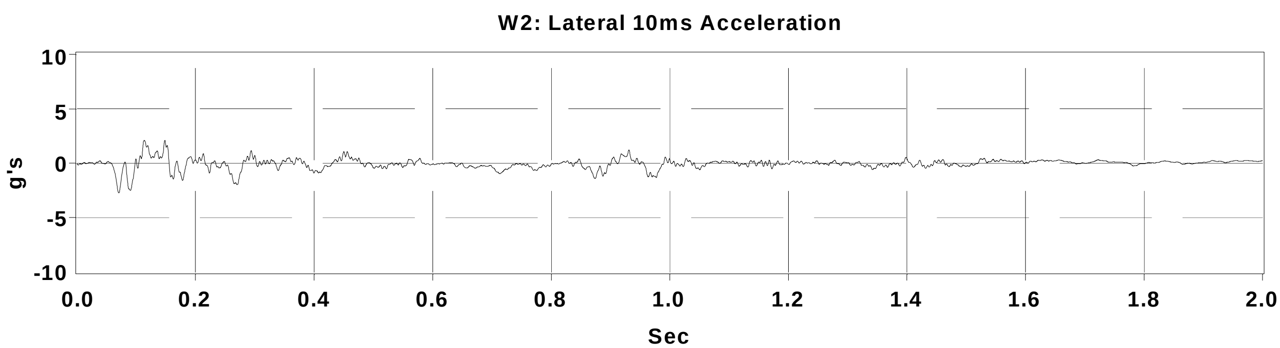


Figure C-22. Vertical g-Trace/Occupant Kinematics - Test 71-1776-001





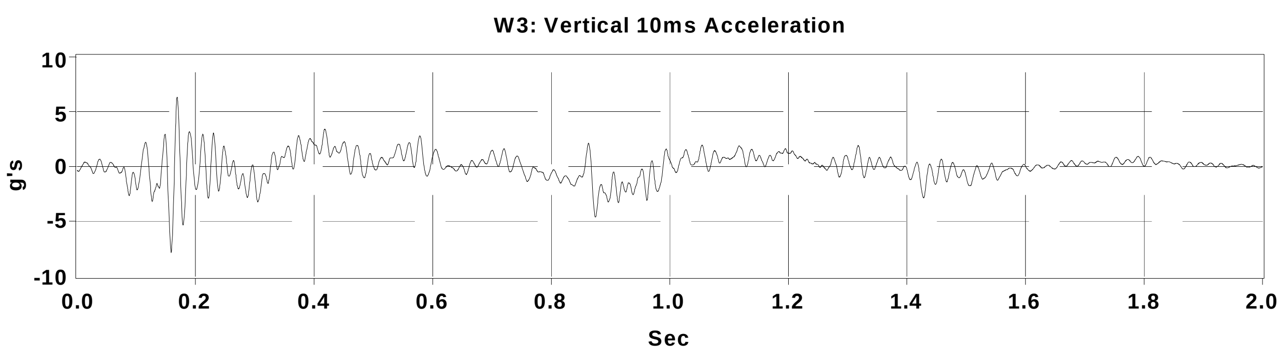


Figure C-23. 10 ms Average Vehicle Accelerations - Test 71-1776-001

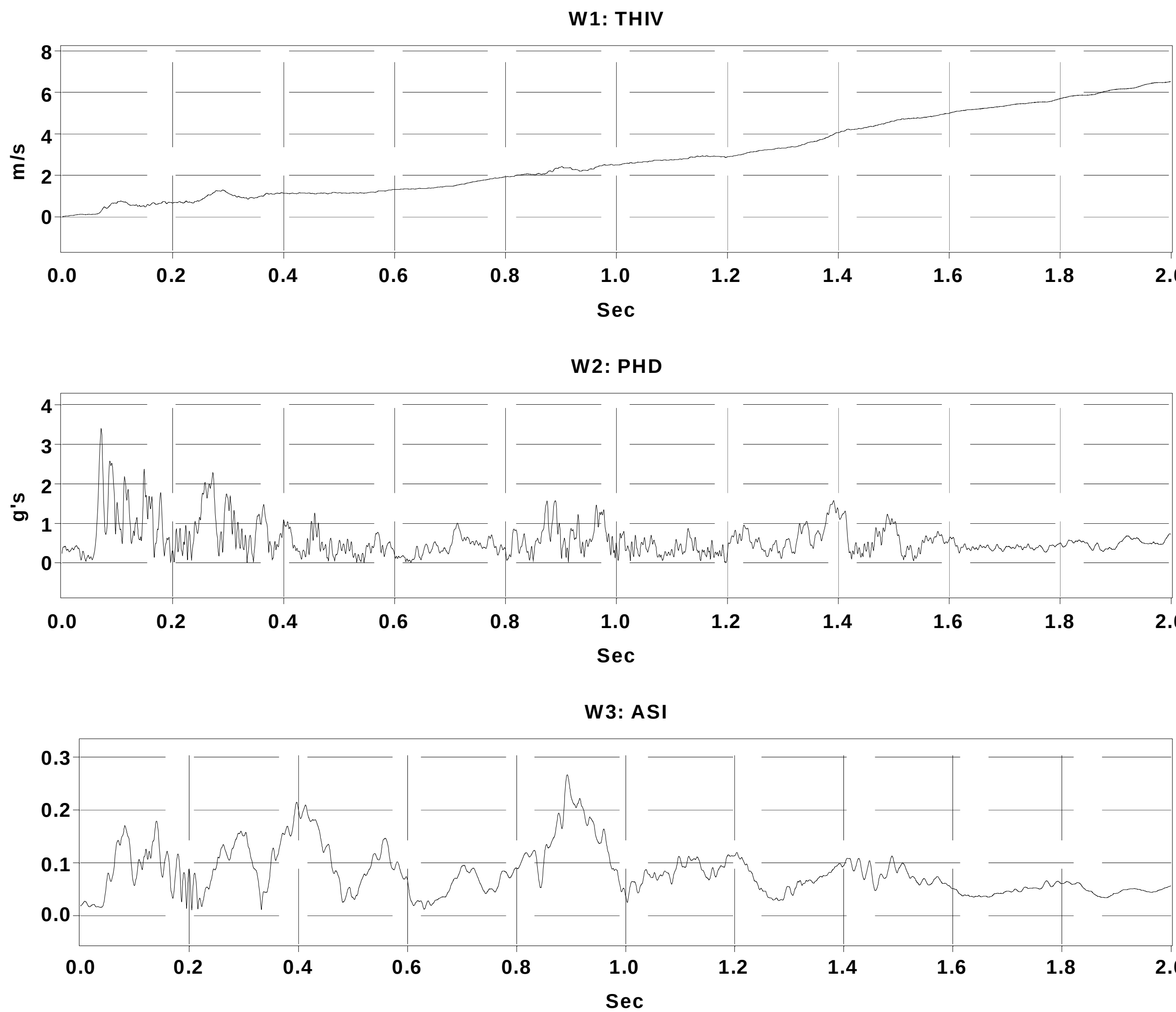


Figure C-24. THIV, PHD, and ASI - Test 71-1776-001

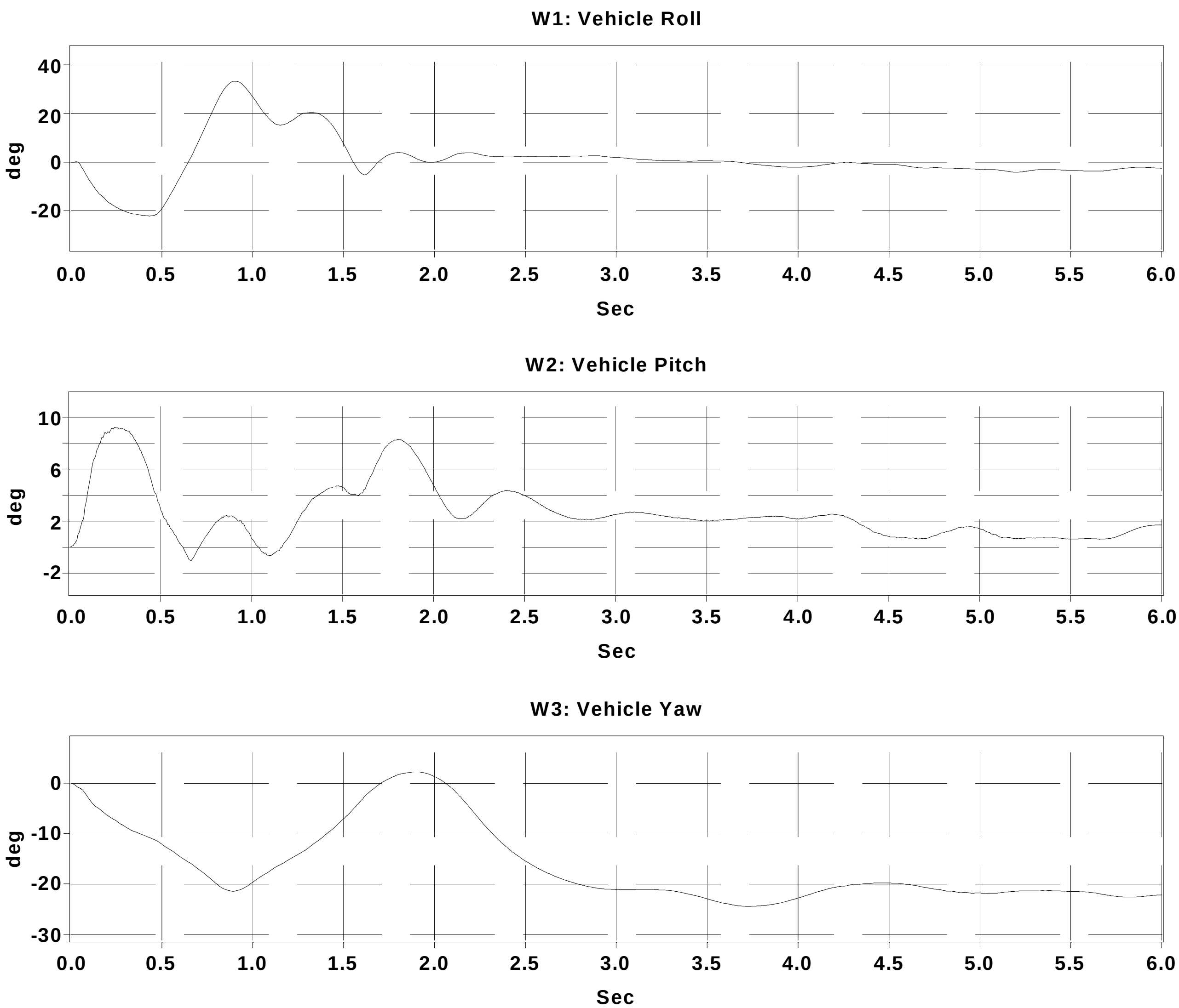


Figure C-25. Vehicular Angular Displacements - Test 71-1776-003

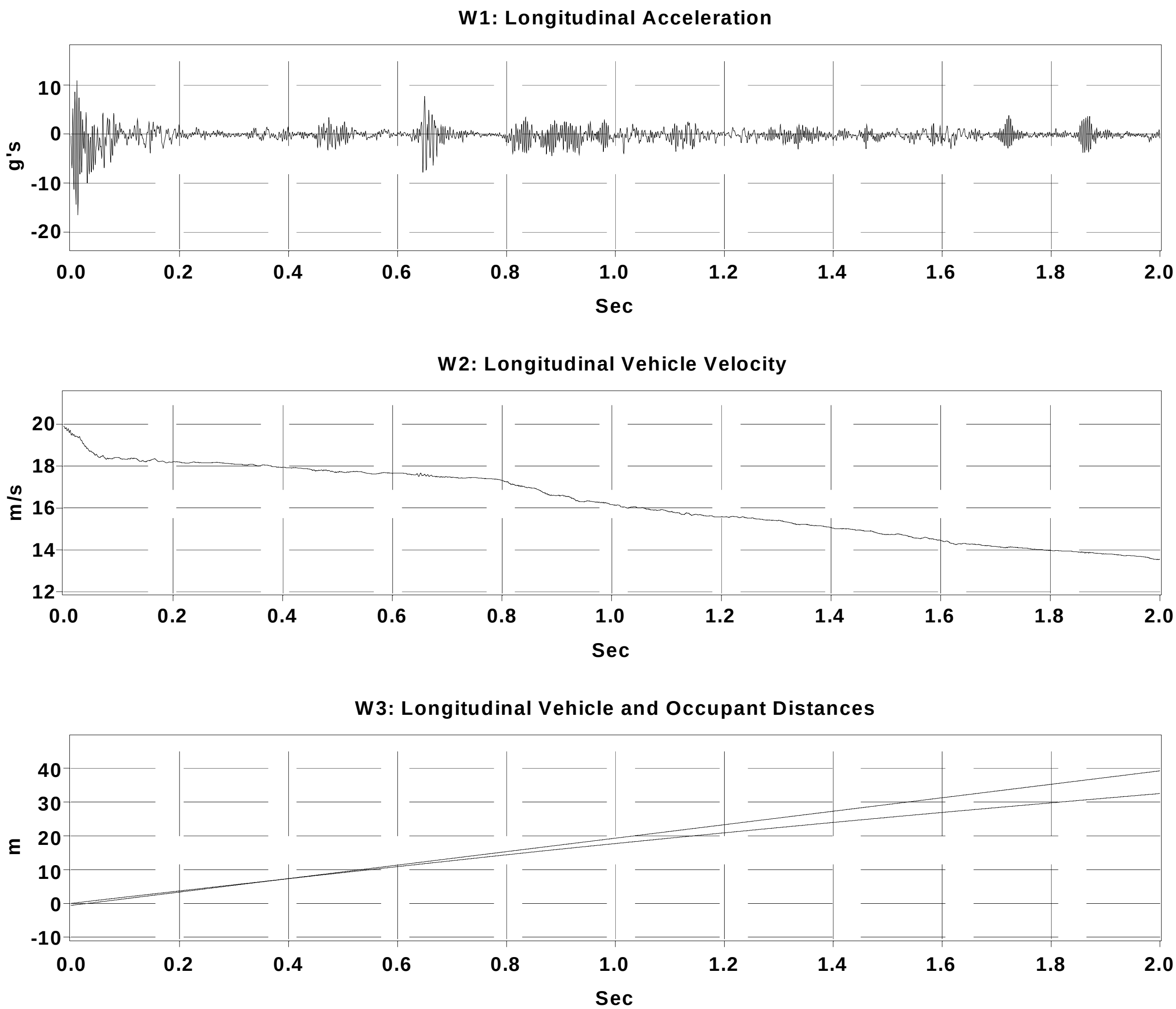


Figure C-26. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-003

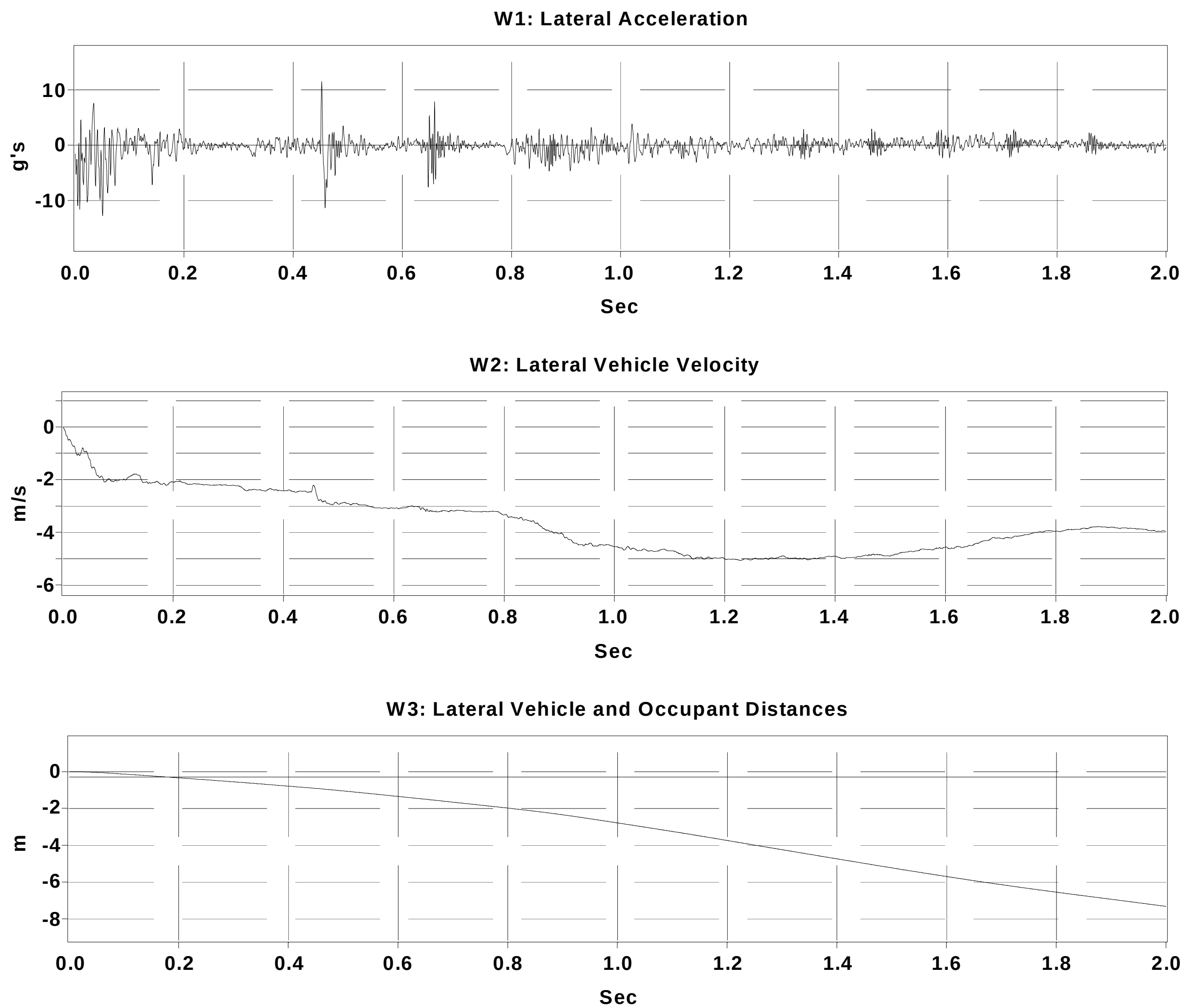


Figure C-27. Lateral g-Trace/Occupant Kinematics - Test 71-1776-003

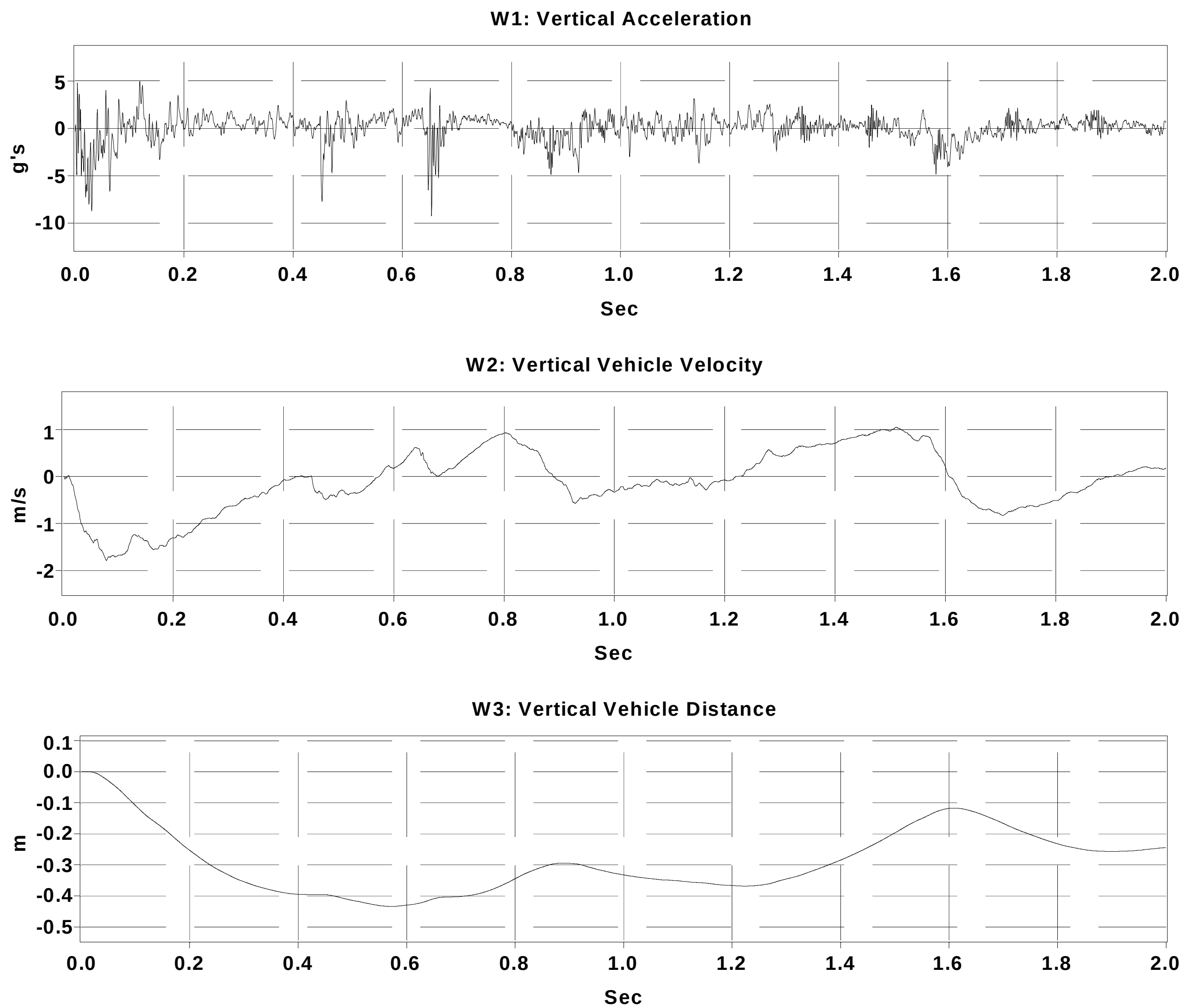


Figure C-28. Vertical g-Trace/Occupant Kinematics - Test 71-1776-003

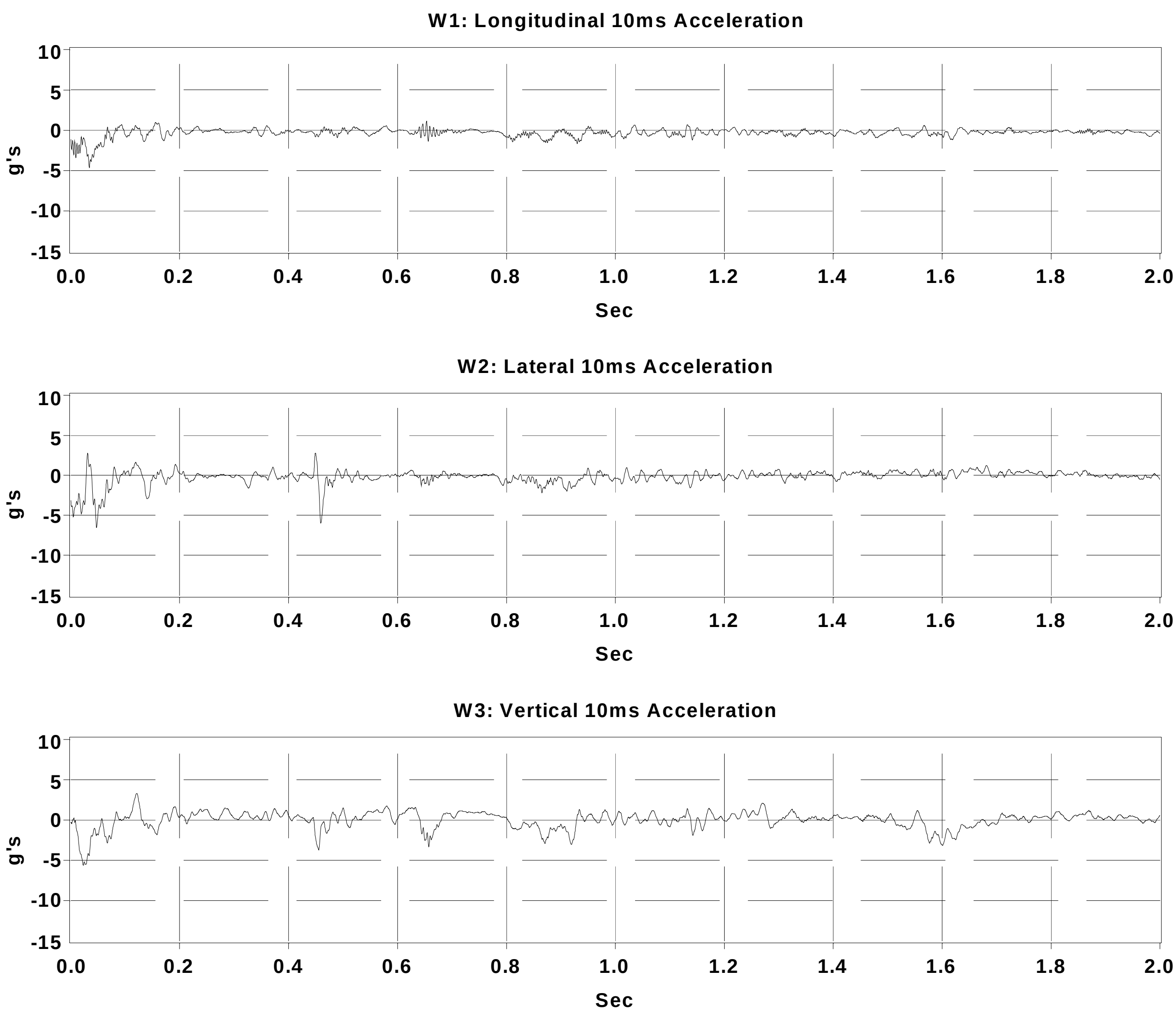


Figure C-29. 10 ms Average Vehicle Accelerations - Test 71-1776-003

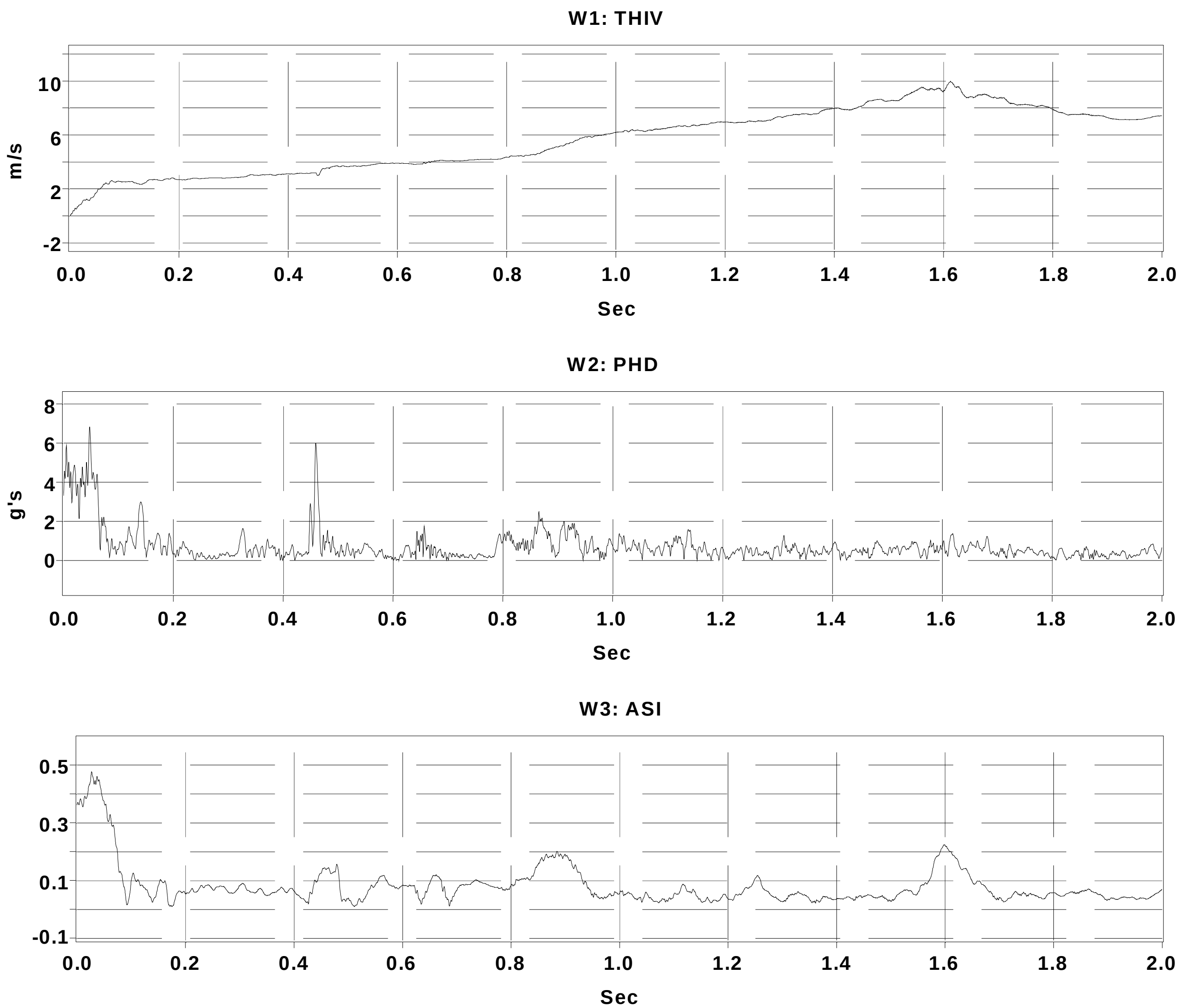


Figure C-30. THIV, PHD, and ASI - Test 71-1776-003

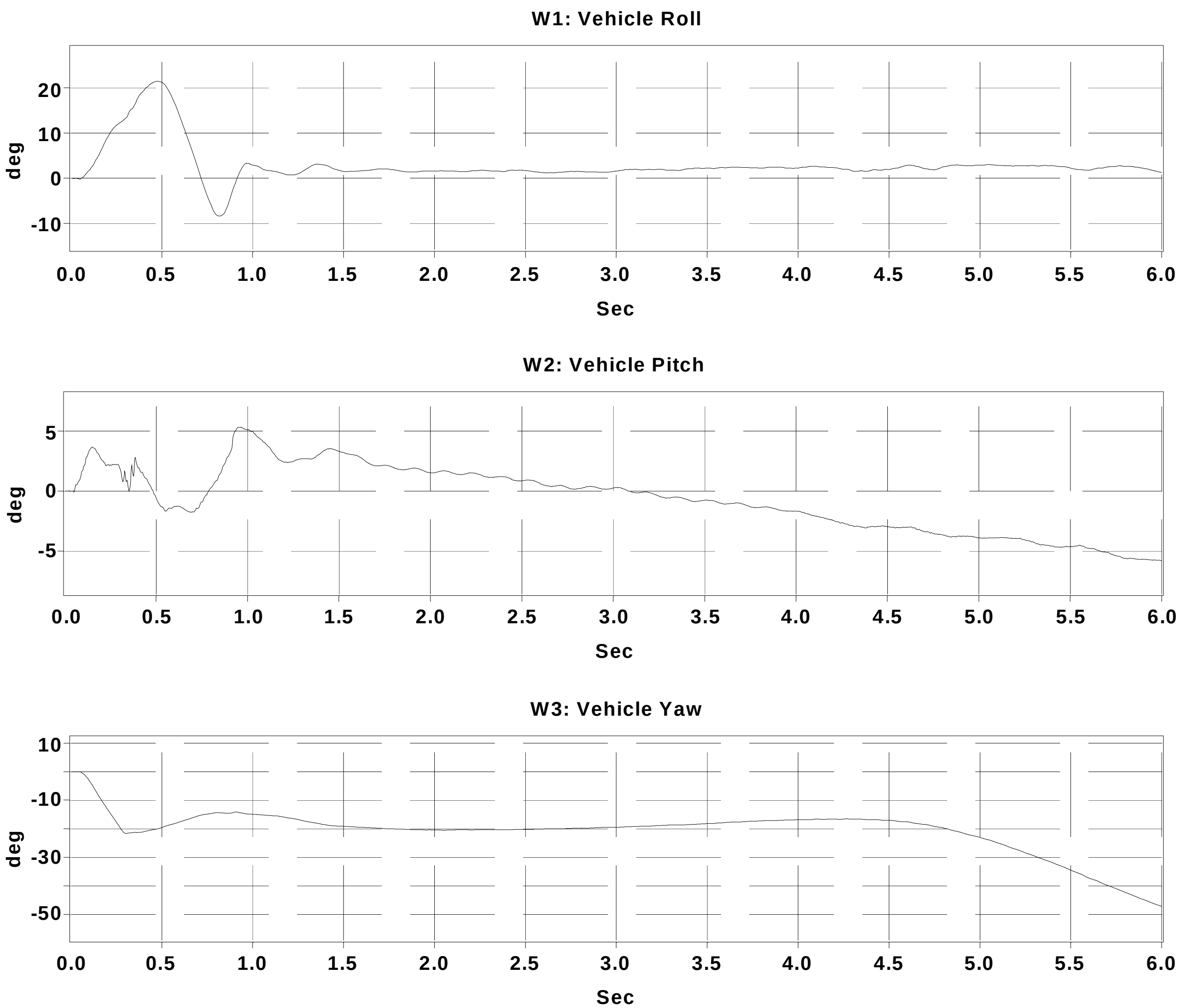


Figure C-31. Vehicular Angular Displacements - Test 71-1776-006

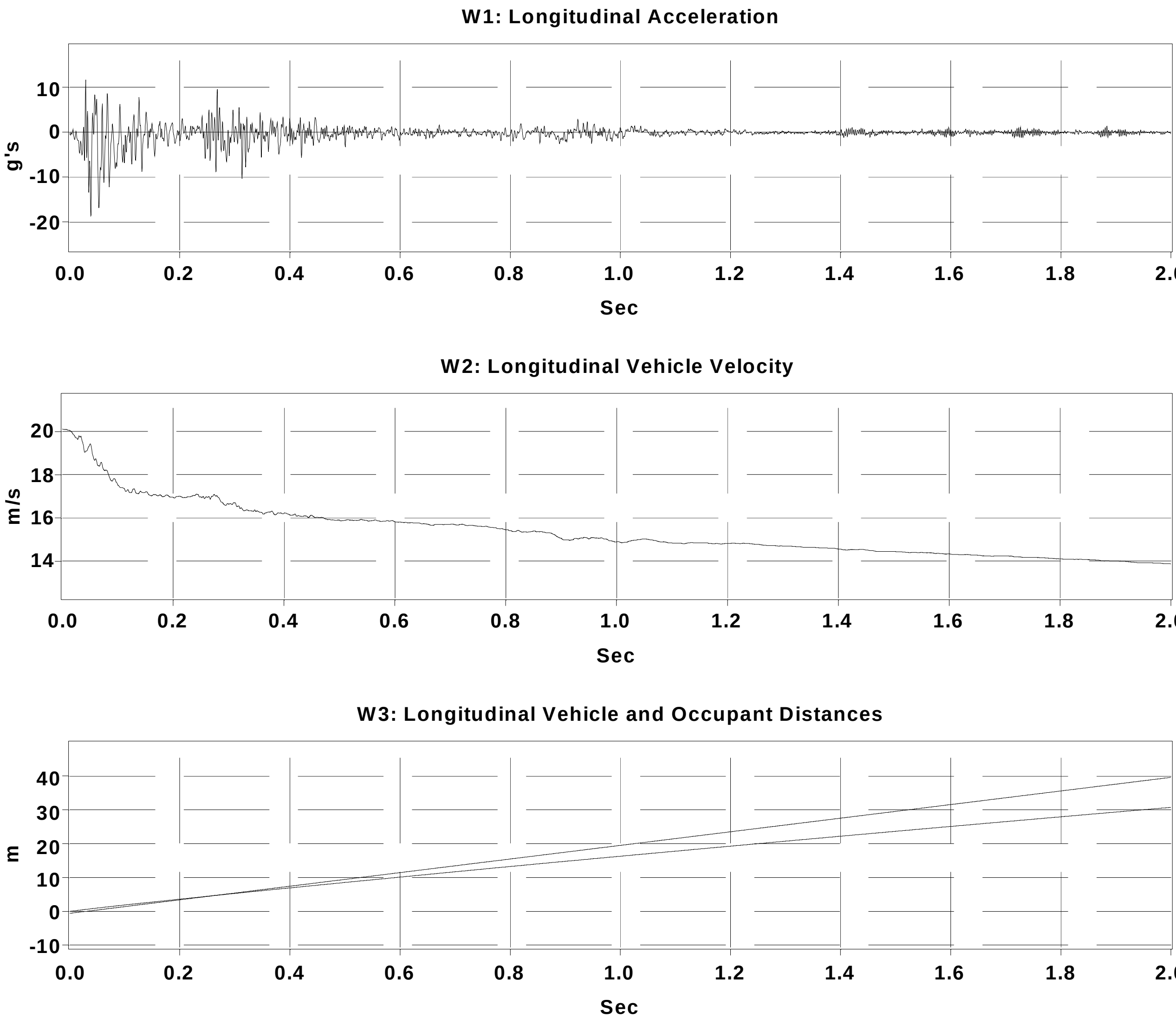


Figure C-32. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-006

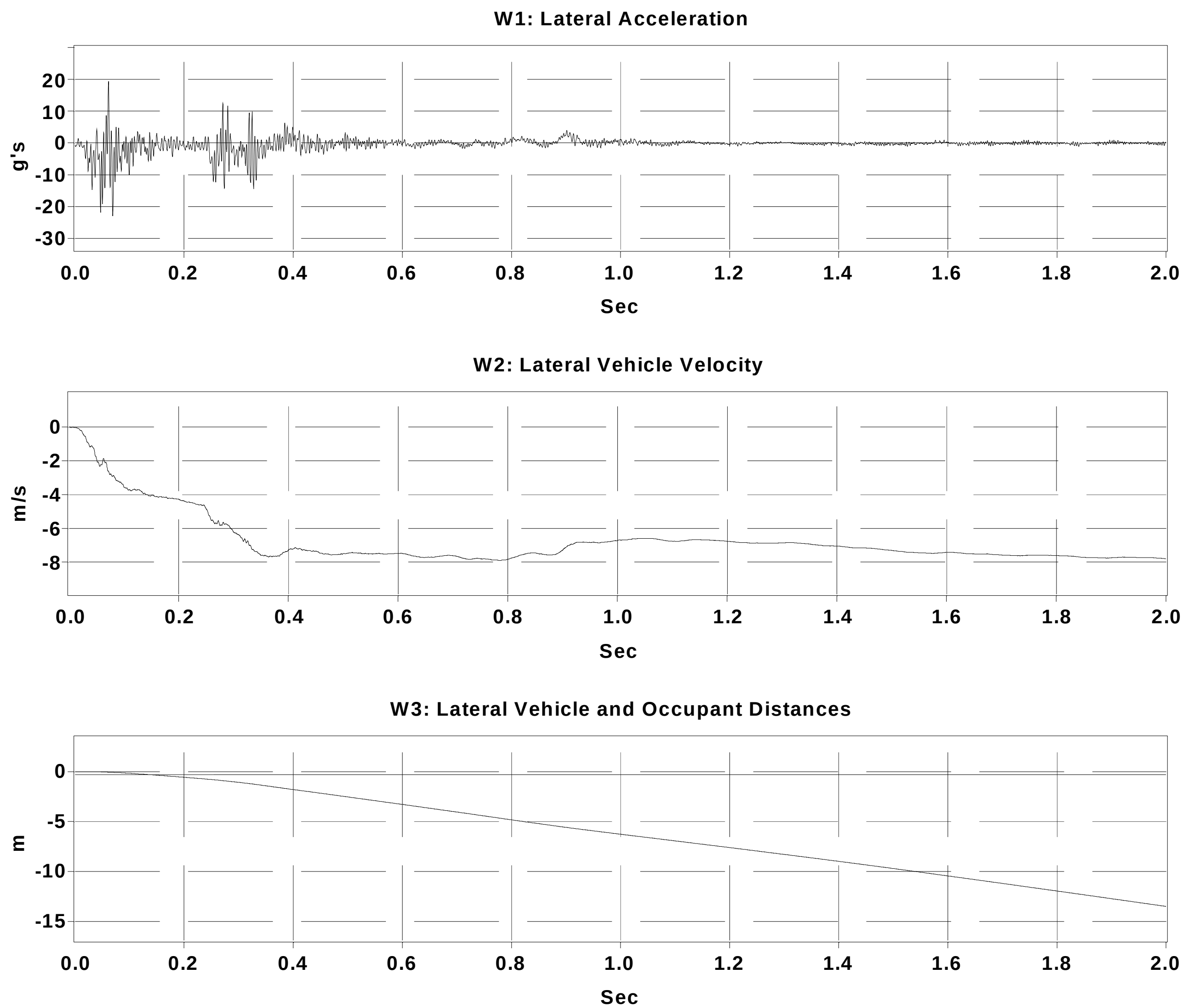


Figure C-33. Lateral g-Trace/Occupant Kinematics - Test 71-1776-006

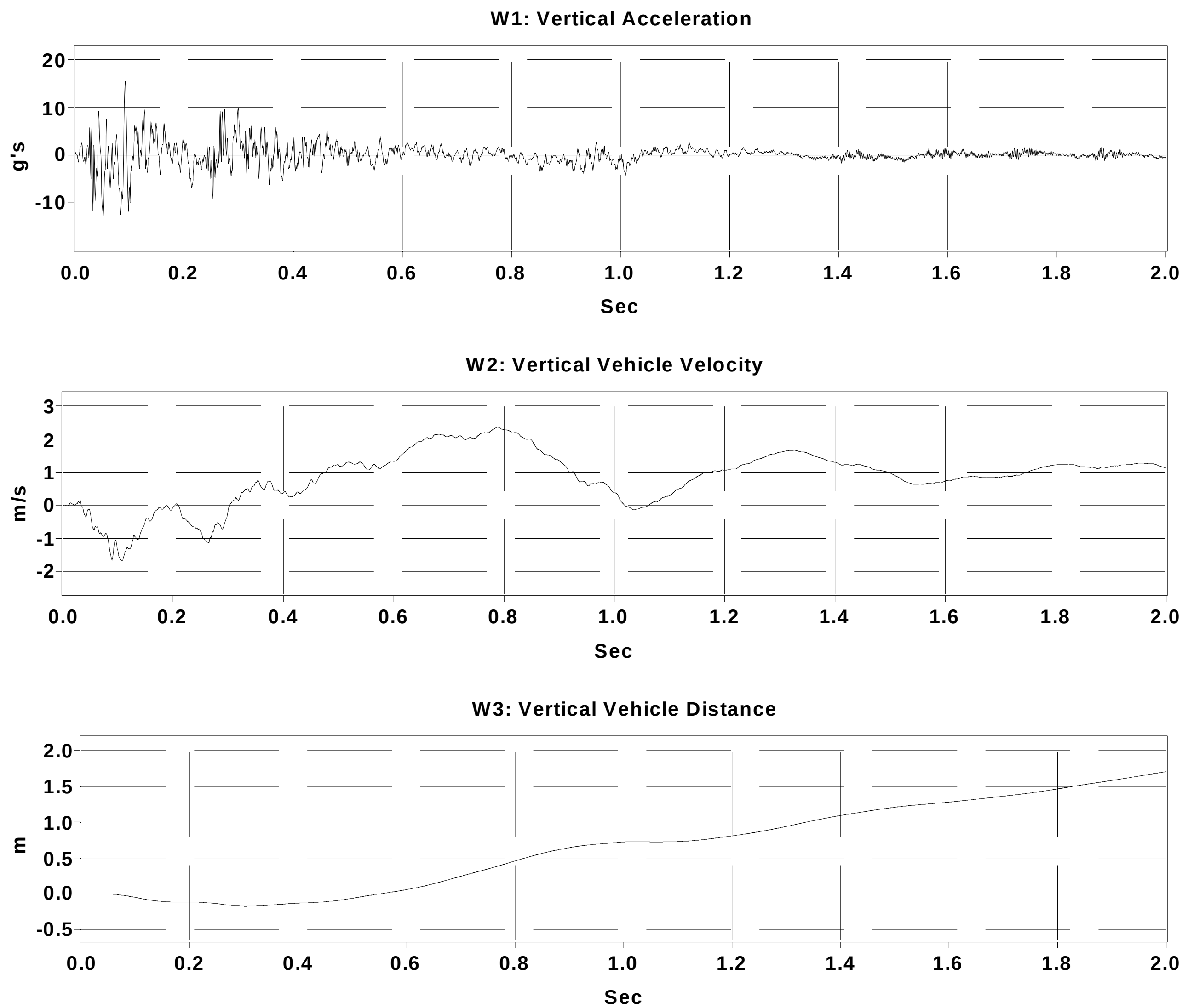
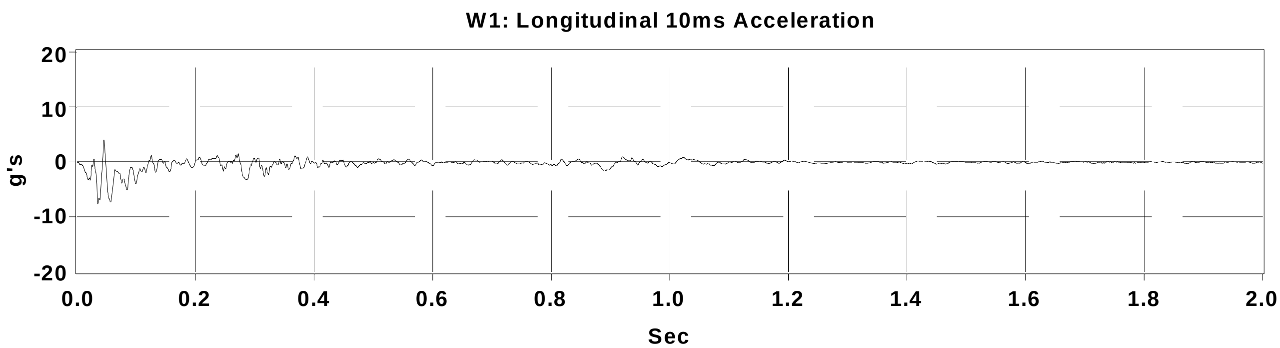
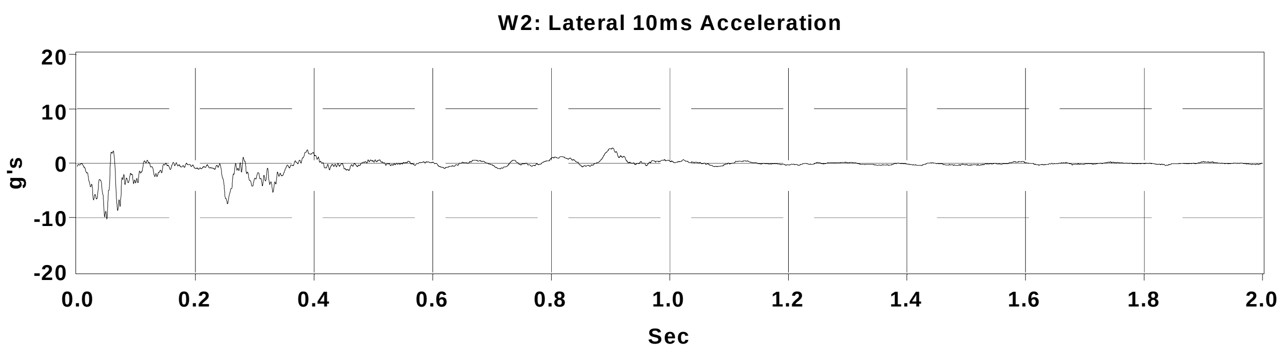


Figure C-34. Vertical g-Trace/Occupant Kinematics - Test 71-1776-006





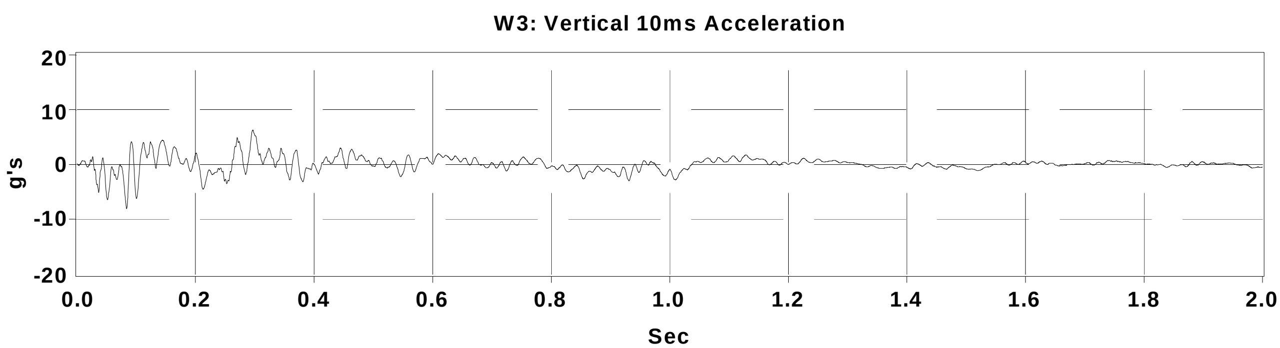


Figure C-35. 10 ms Average Vehicle Accelerations - Test 71-1776-006

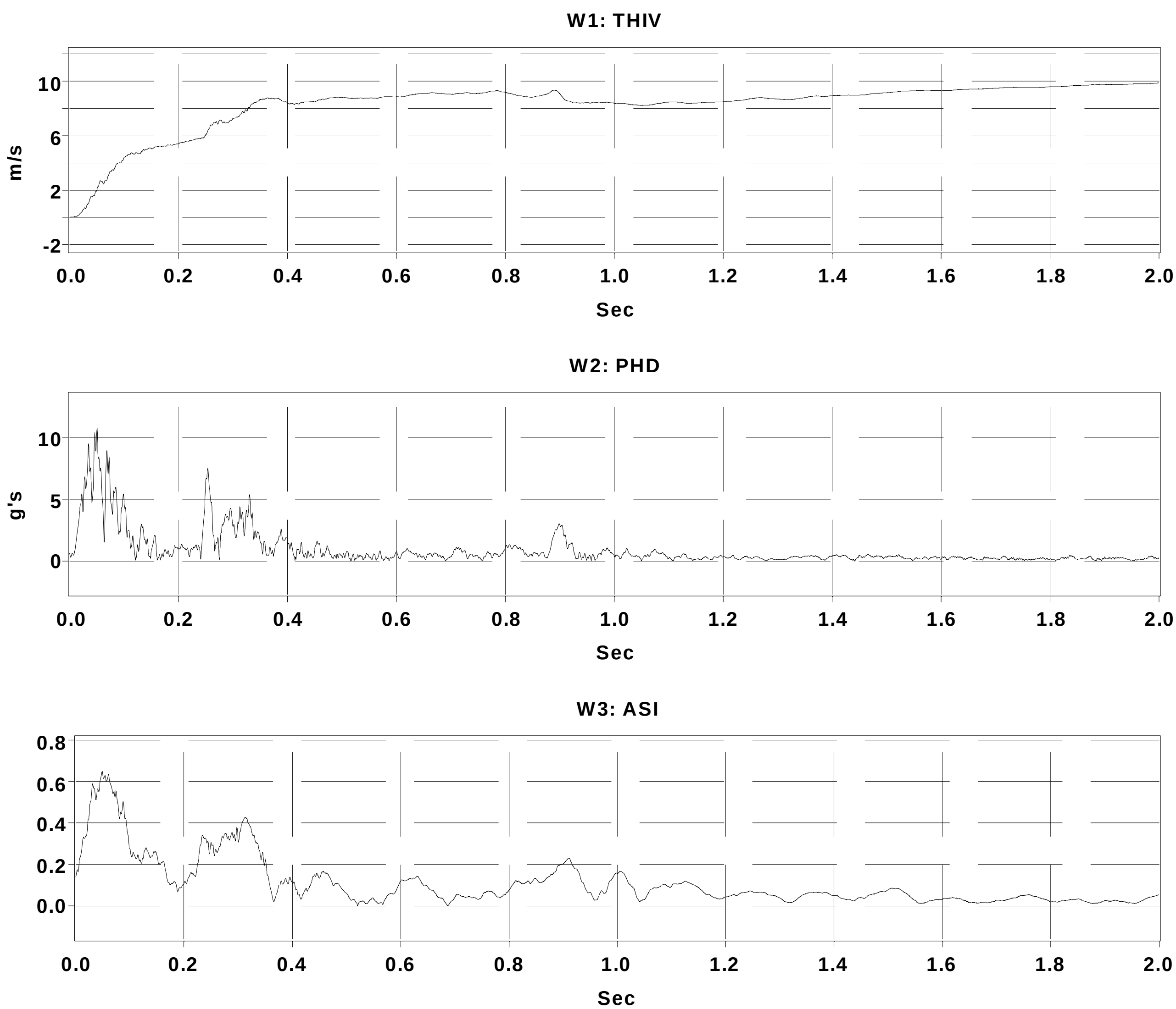


Figure C-36. THIV, PHD, and ASI - Test 71-1776-006

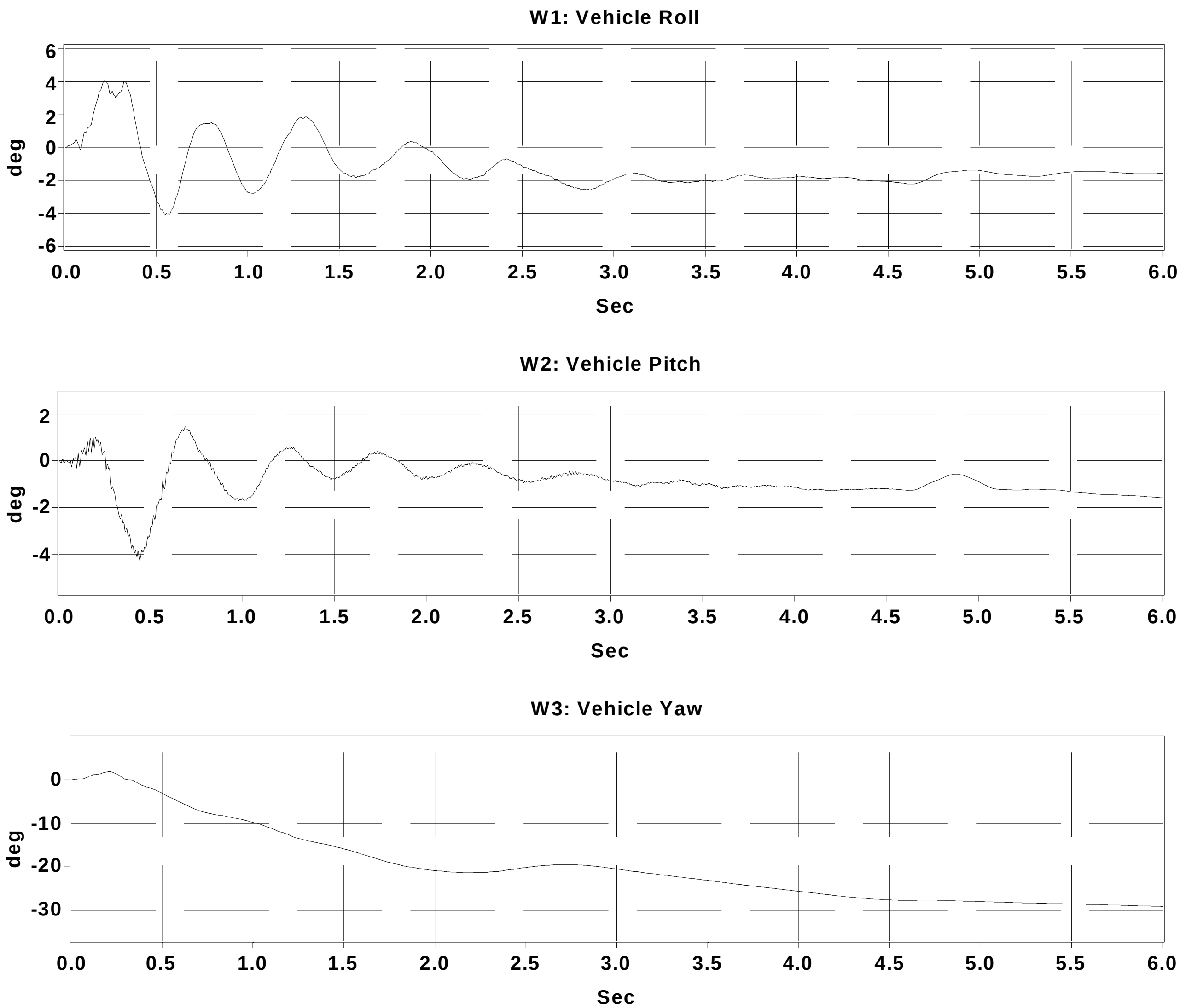


Figure C-37. Vehicular Angular Displacements - Test 71-1776-007

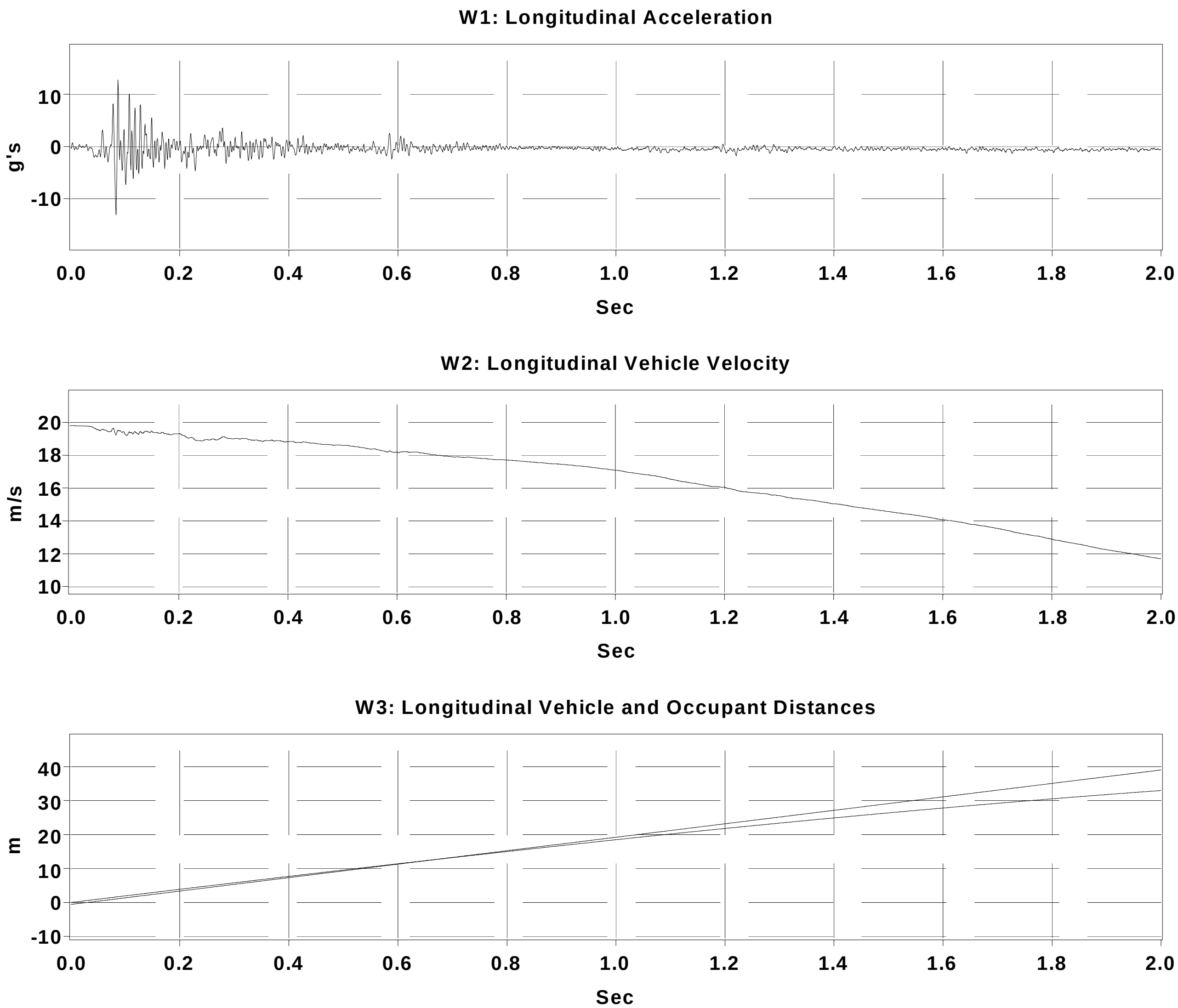
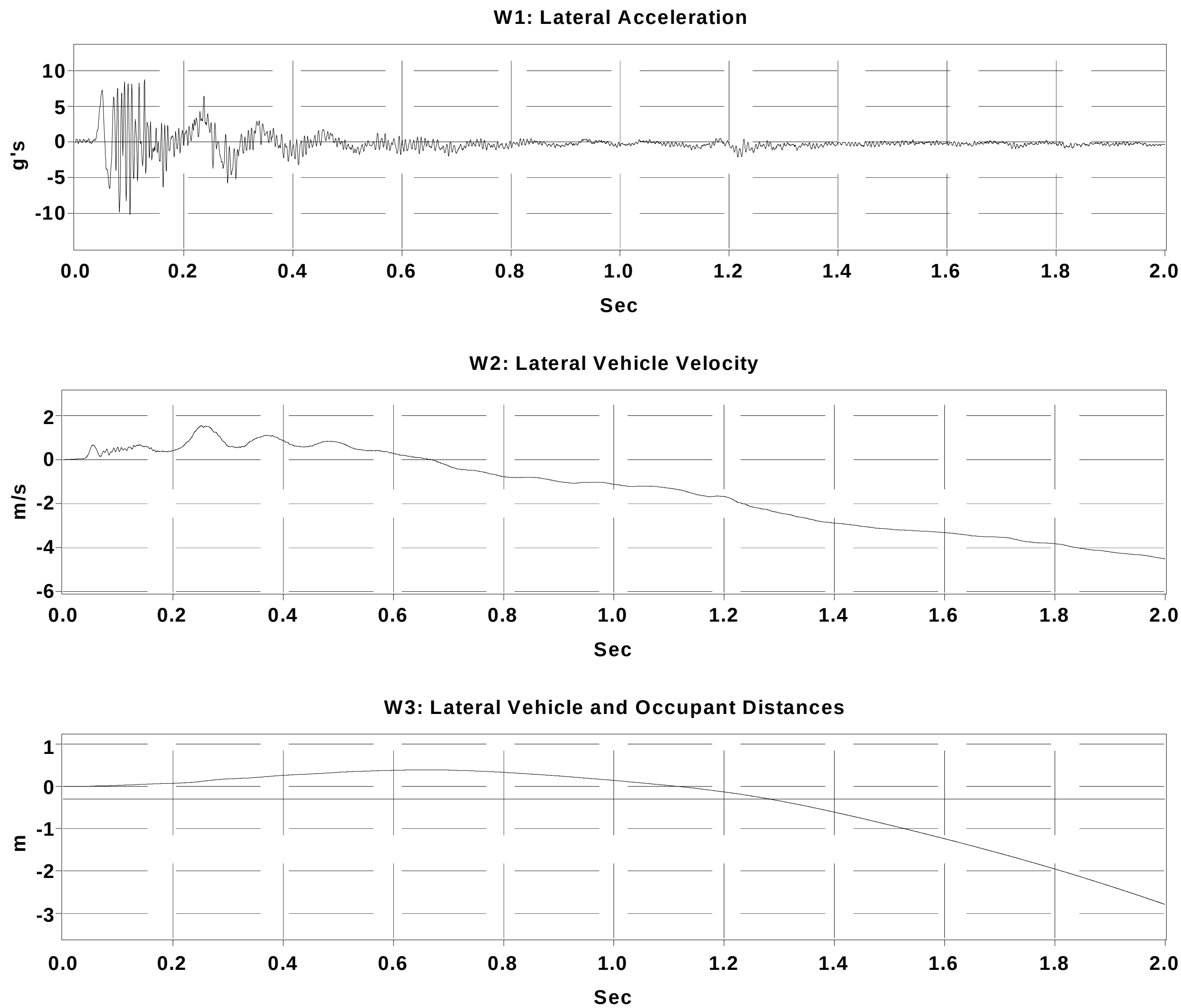


Figure C-38. Longitudinal g-Trace/Occupant Kinematics - Test 71-1776-007



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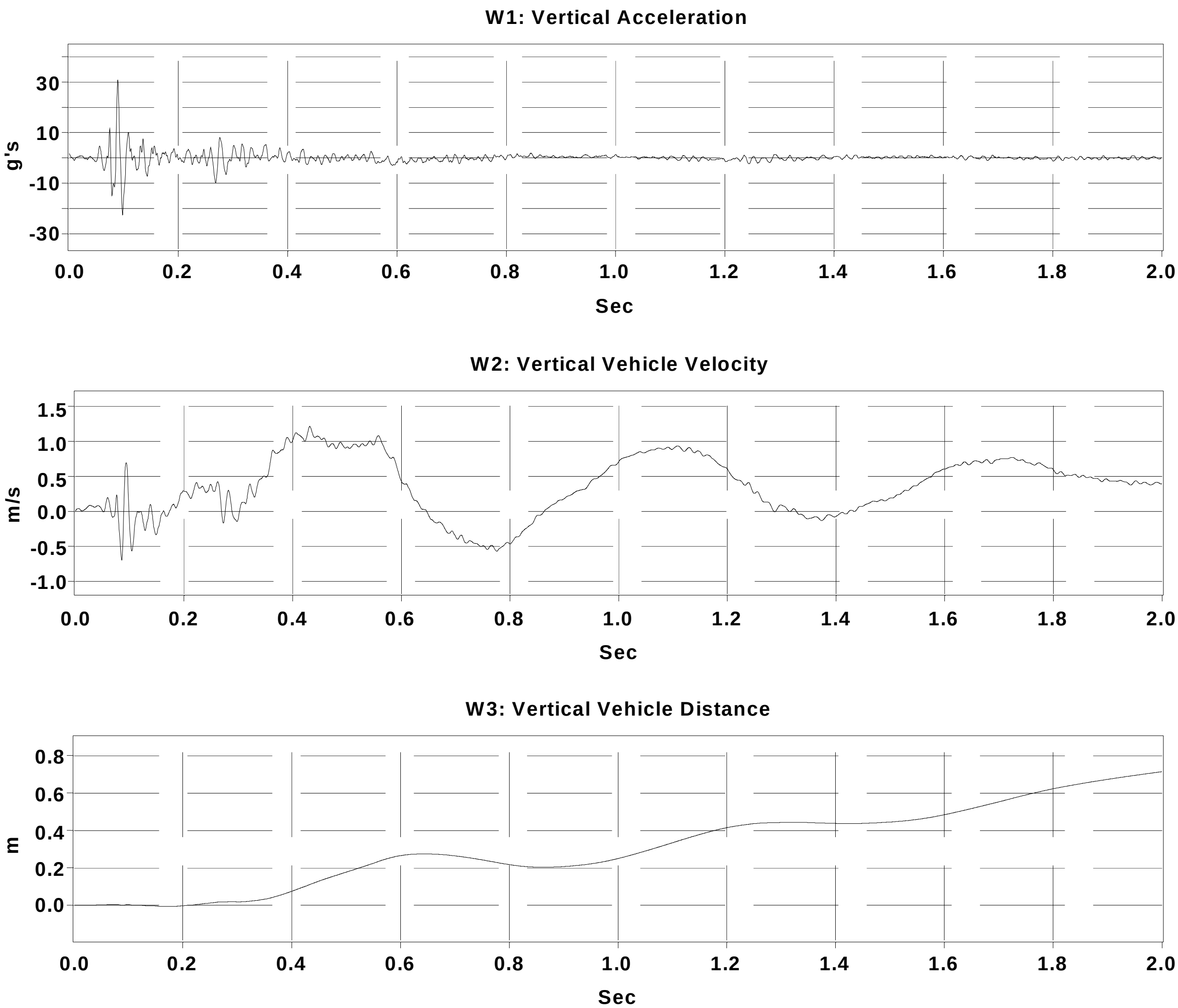

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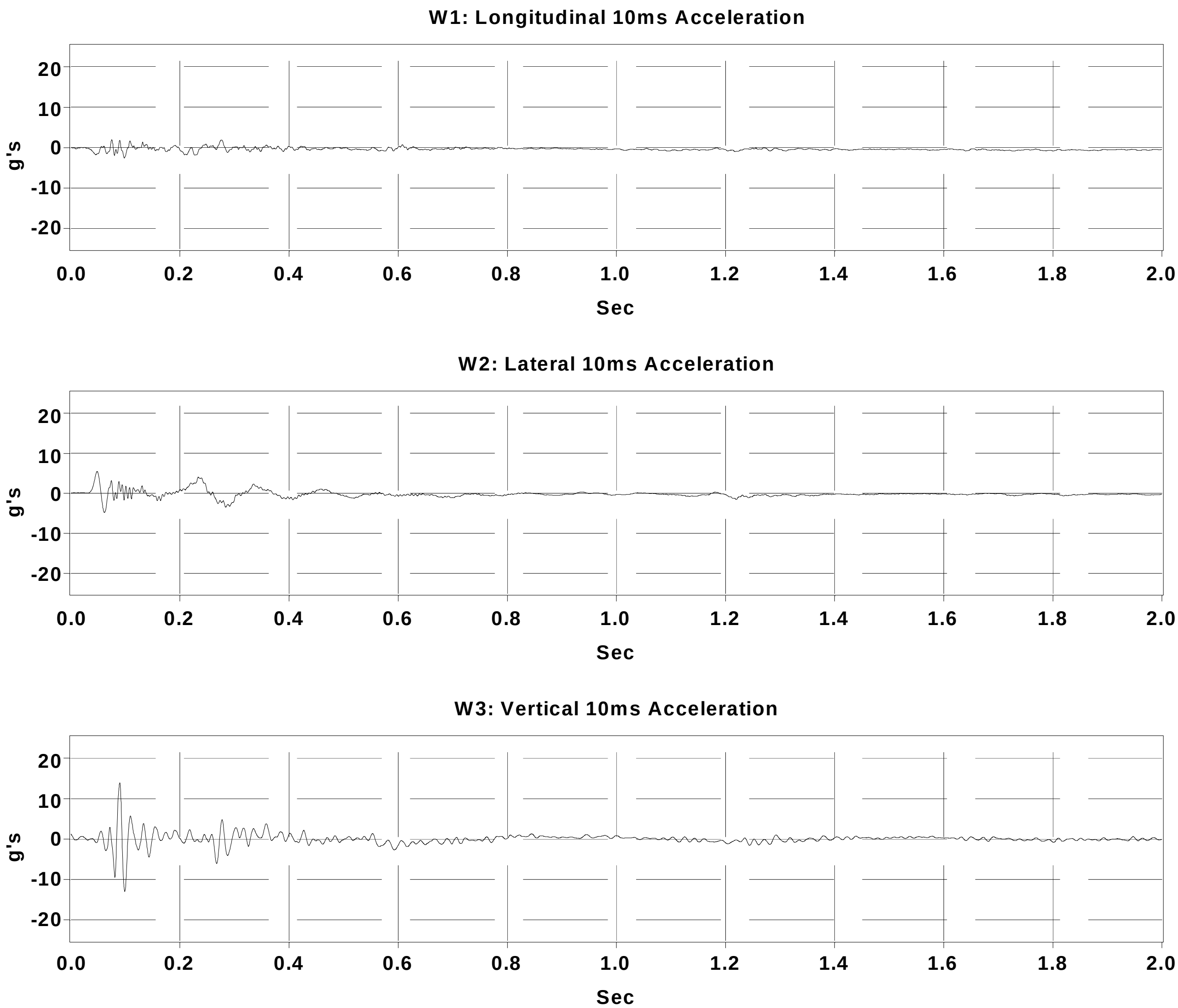

Figure C-41. 10 ms Average Vehicle Accelerations - Test 71-1776-007

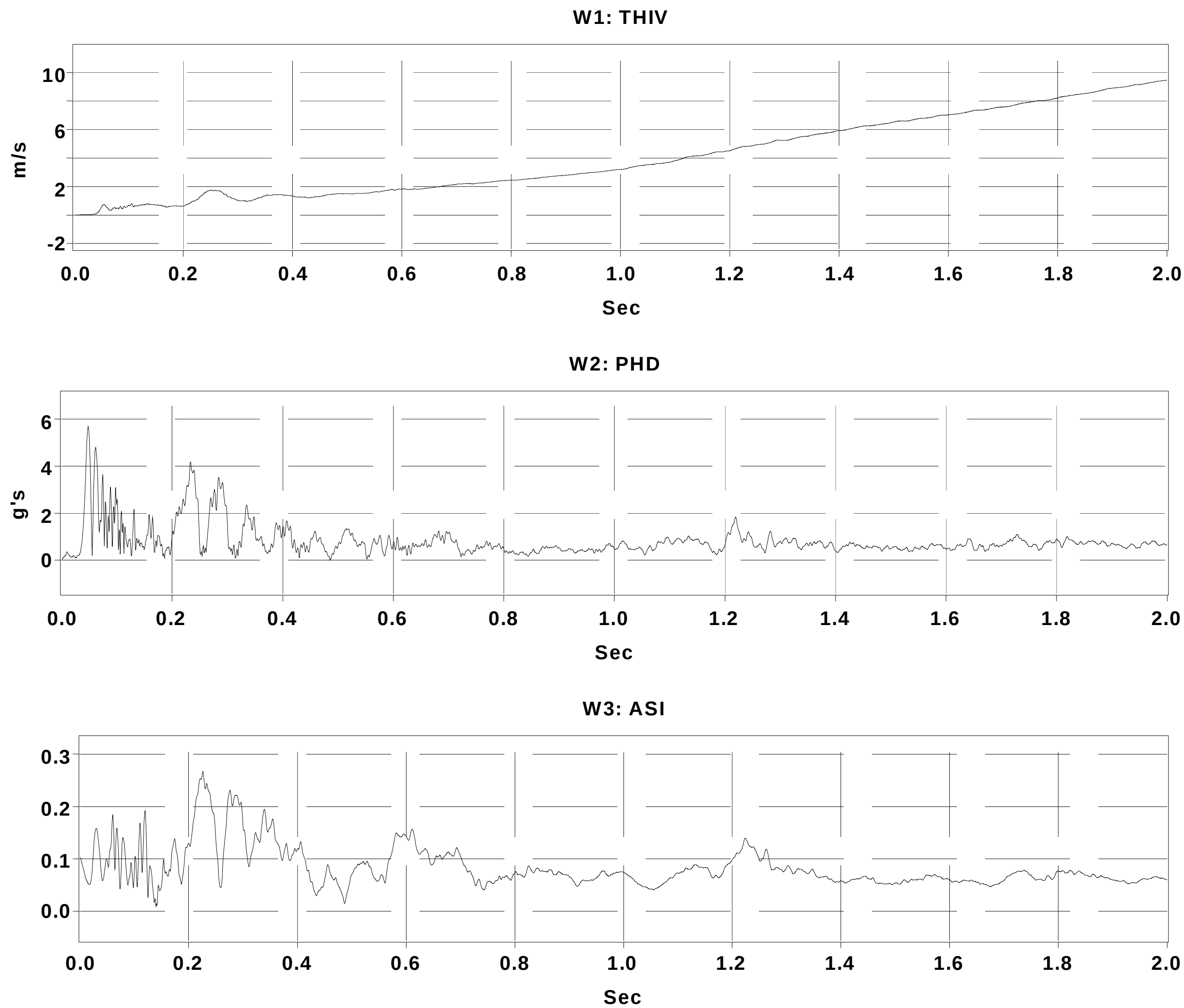

Figure C-42. THIV, PHD, and ASI - Test 71-1776-007

UNIVERSITY OF FLORIDA
TAPERED END TREATMENT FOR LOW-PROFILE BARRIER WALL

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GENERAL NOTES:

1. CONCRETE
   A. CONCRETE MIX:
      f'c'i = 3,000 psi AT FORM REMOVAL
      f'c = 5,000 psi AT 28 DAYS.

   B. CURING SHALL BE IN ACCORDANCE WITH CURRENT FLORIDA DOT STANDARDS.

   C. NEITHER TRANSPORT NOR INSTALLATION OF BARRIER SEGMENTS SHALL TAKE PLACE BEFORE THE 28 DAY CONCRETE STRENGTH HAS BEEN ACHIEVED.

2. ALL REBAR SHALL BE A615, GR60.

3. ALL STRUCTURAL STEEL (EXCEPT AS NOTED BELOW) SHALL BE A572 GRADE 50

4. ALL STRUCTURAL STEEL TUBE SHALL BE A500 GRADE B OR C

5. ALL STRUCTURAL STEEL PIPE SHALL BE A53 GRADE B

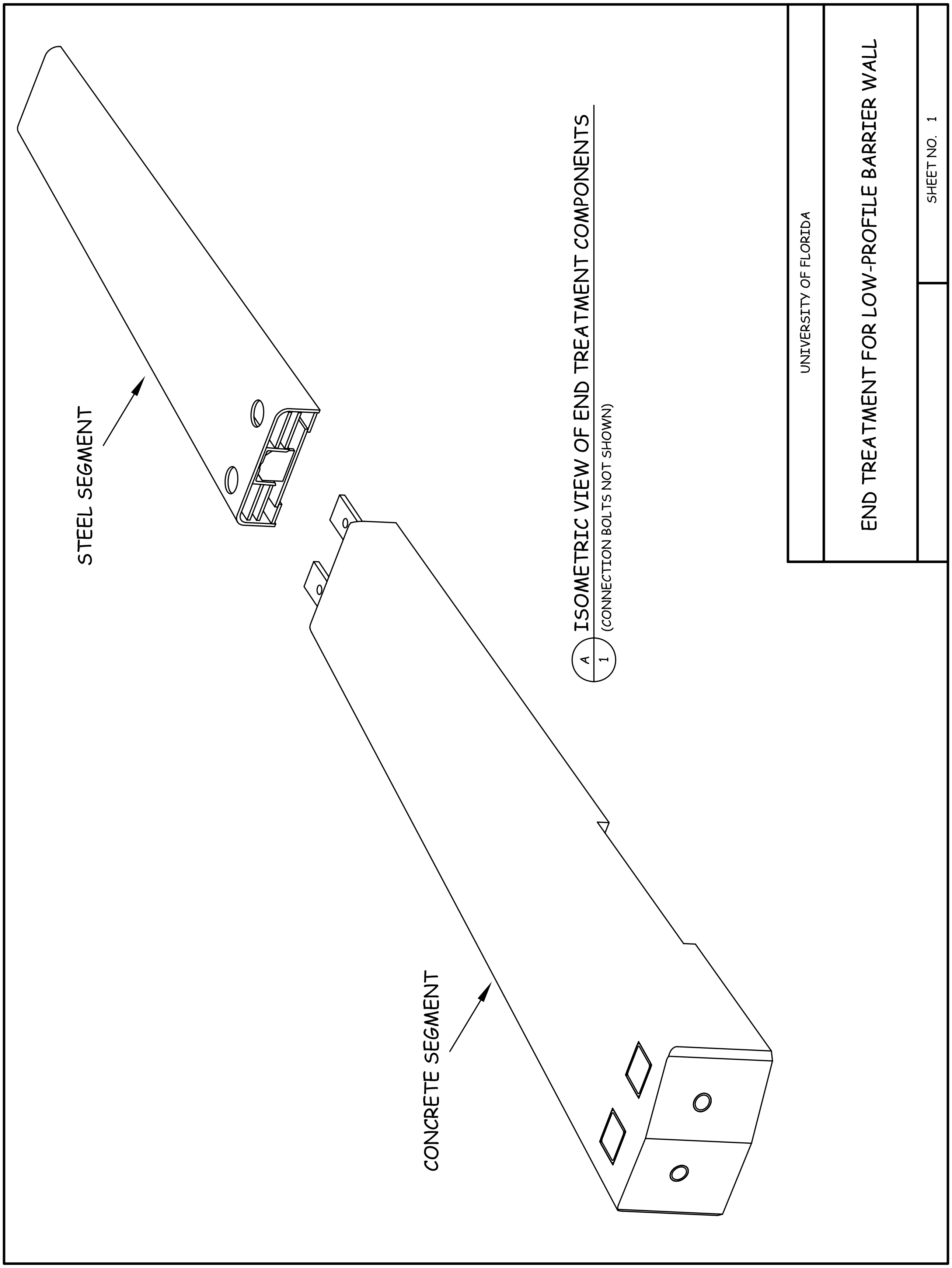
6. FABRICATION OF THE CONCRETE UNITS SHALL CONFORM TO THE REQUIREMENTS OF ACI 318-02.

7. MANUFACTURERS OF CONCRETE UNITS SHALL CONFORM TO THE CURRENT FLORIDA DEPARTMENT OF TRANSPORTATION REQUIREMENTS FOR QUALITY CONTROL. CONTACT THE FLORIDA DEPARTMENT OF TRANSPORTATION, STATE MATERIALS OFFICE FOR INFORMATION ON CURRENT REQUIREMENTS (352-955-6683).

UNIVERSITY OF FLORIDA

END TREATMENT FOR LOW-PROFILE BARRIER WALL

Illustration D-1. Drawings of Florida Concrete Curb End Treatment (1 of 14)



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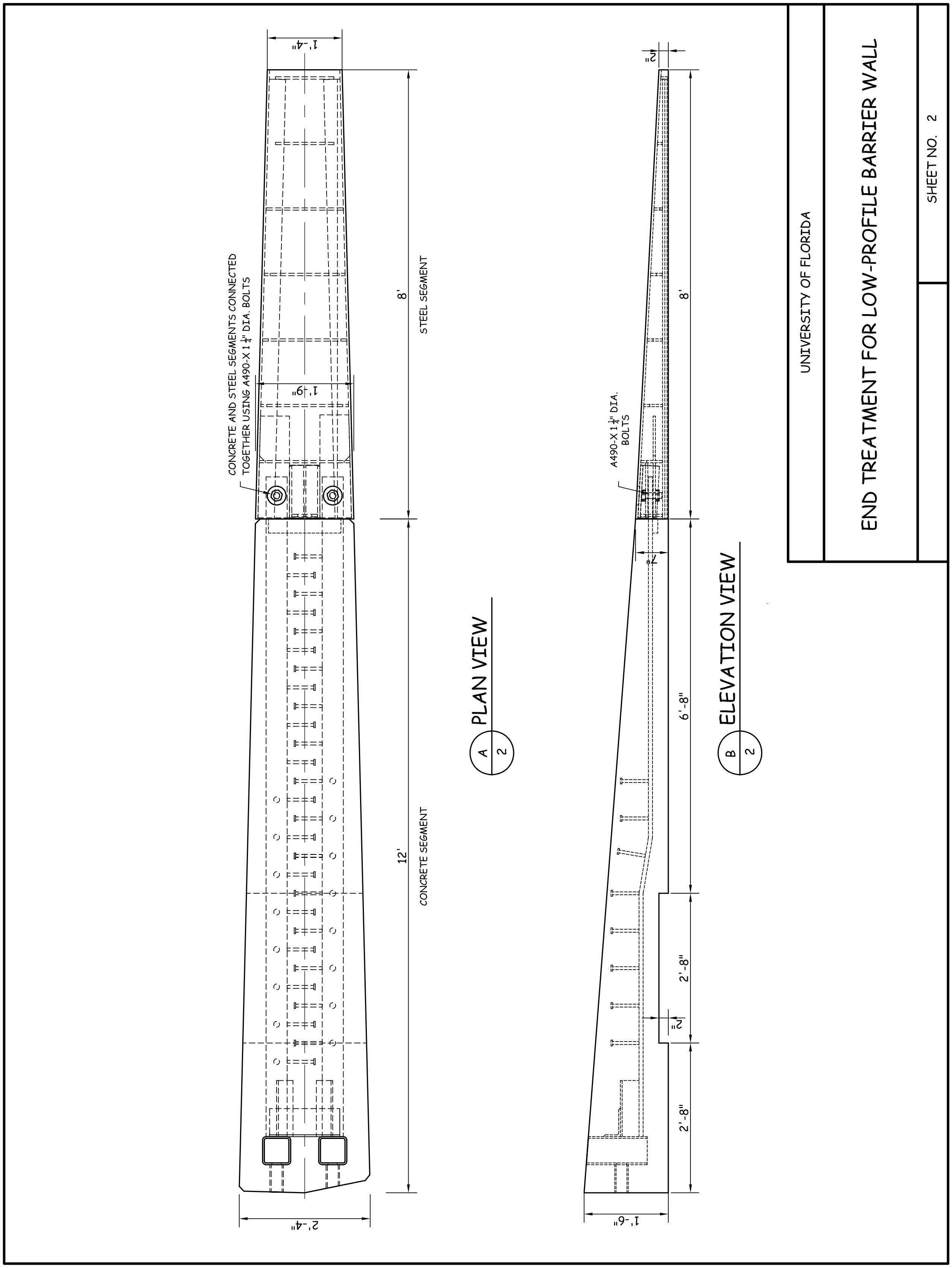

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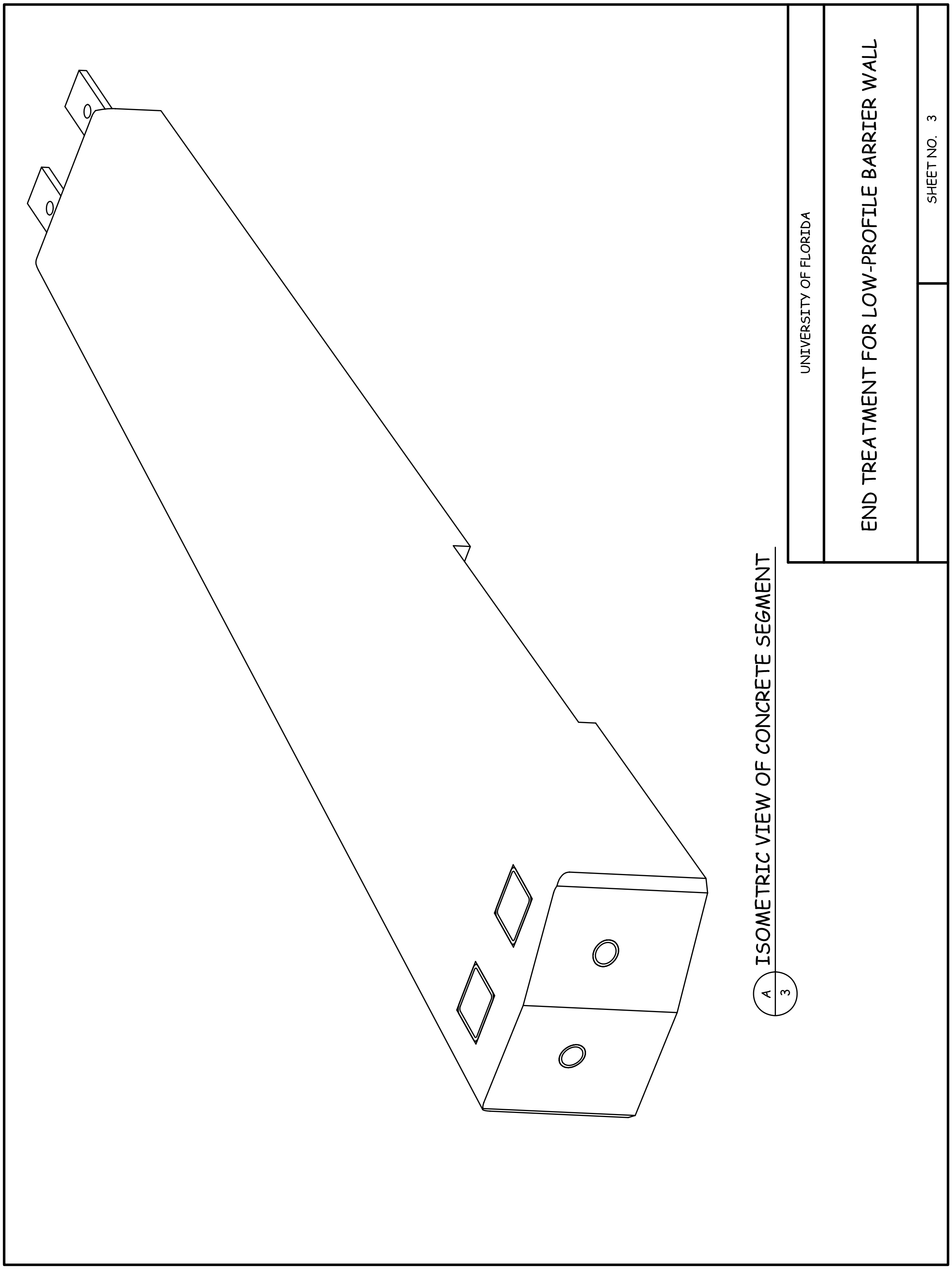

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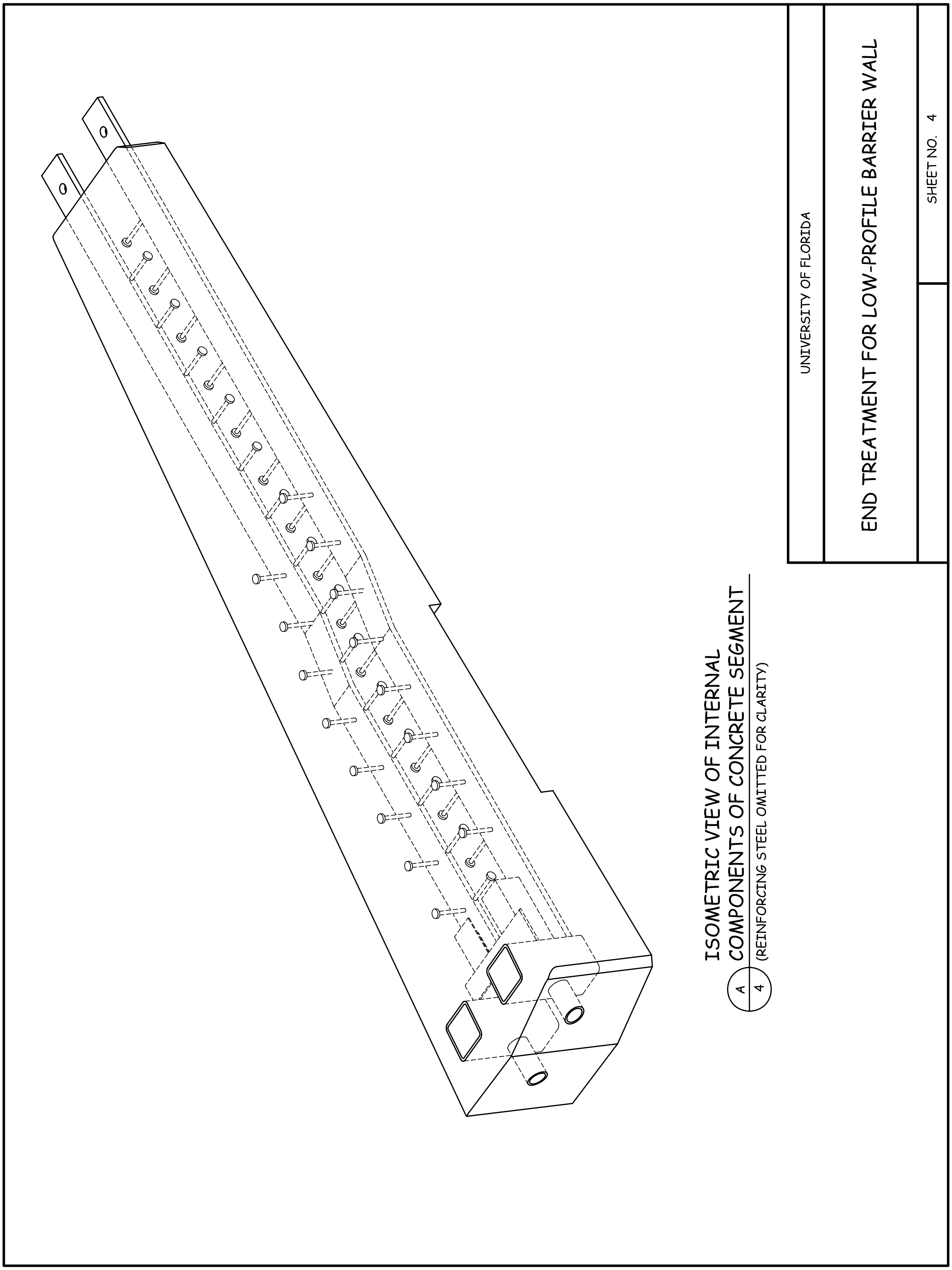

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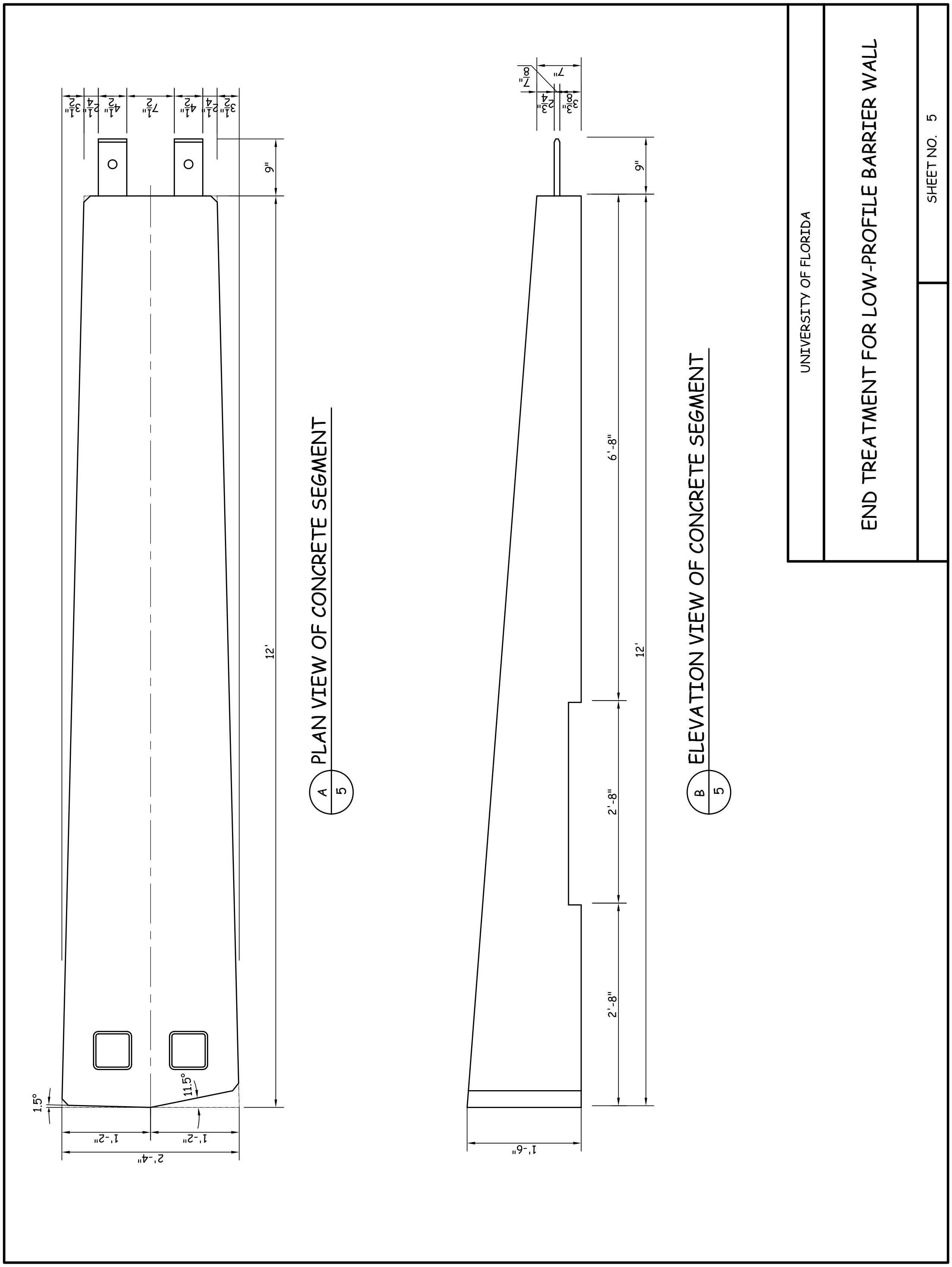
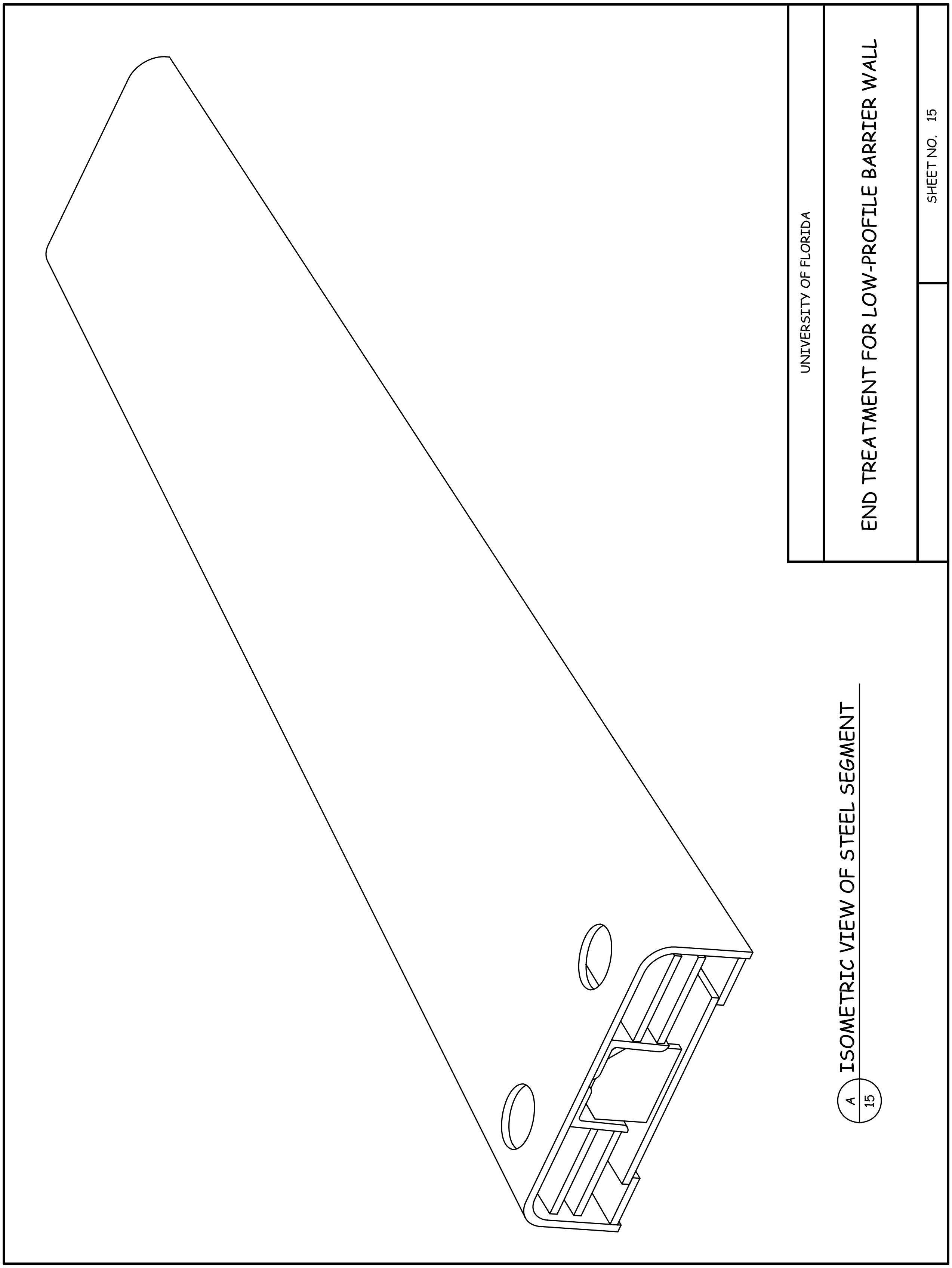


Illustration D-1. Drawings of Florida Concrete Curb End Treatment (6 of 14)



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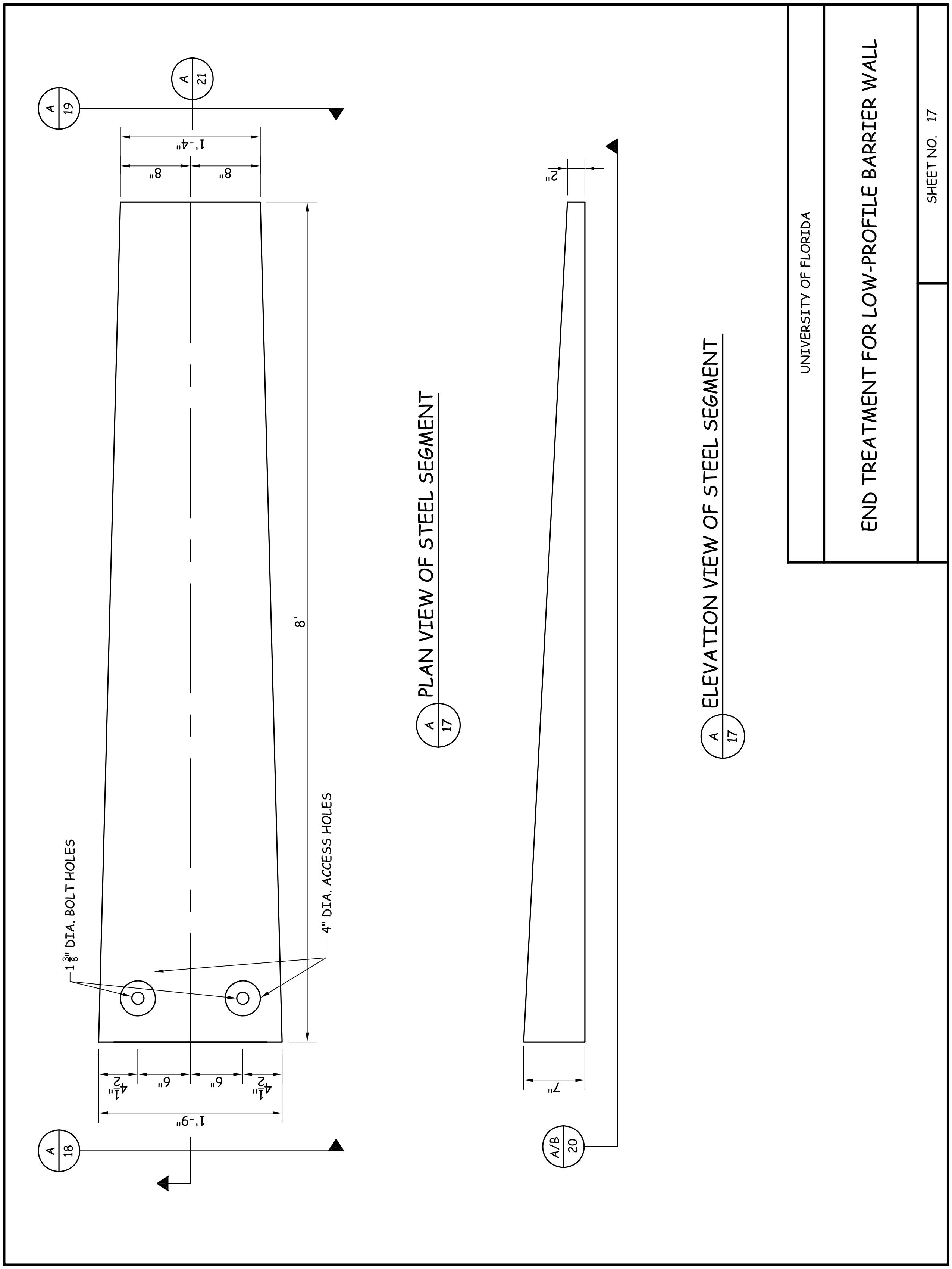

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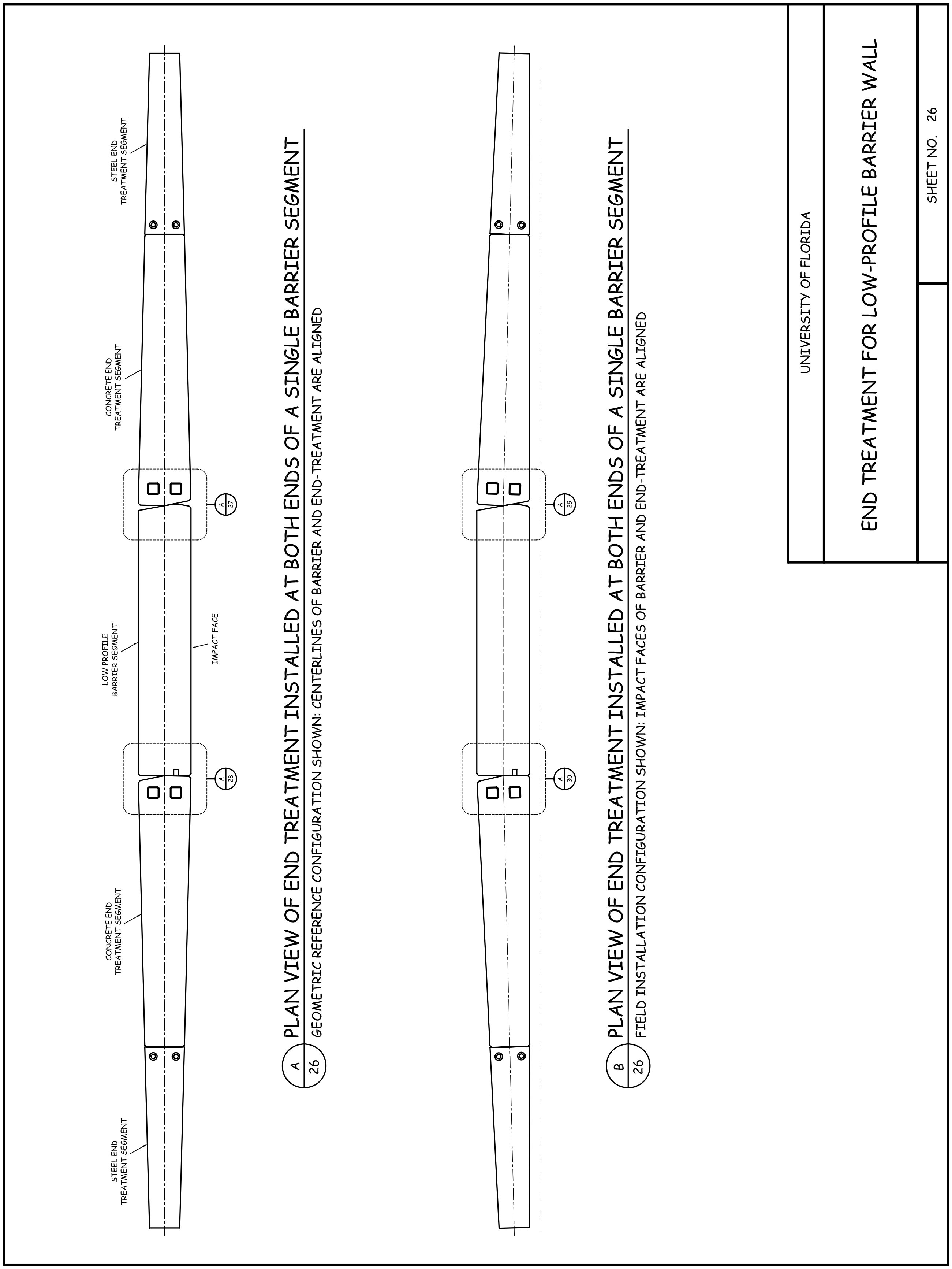

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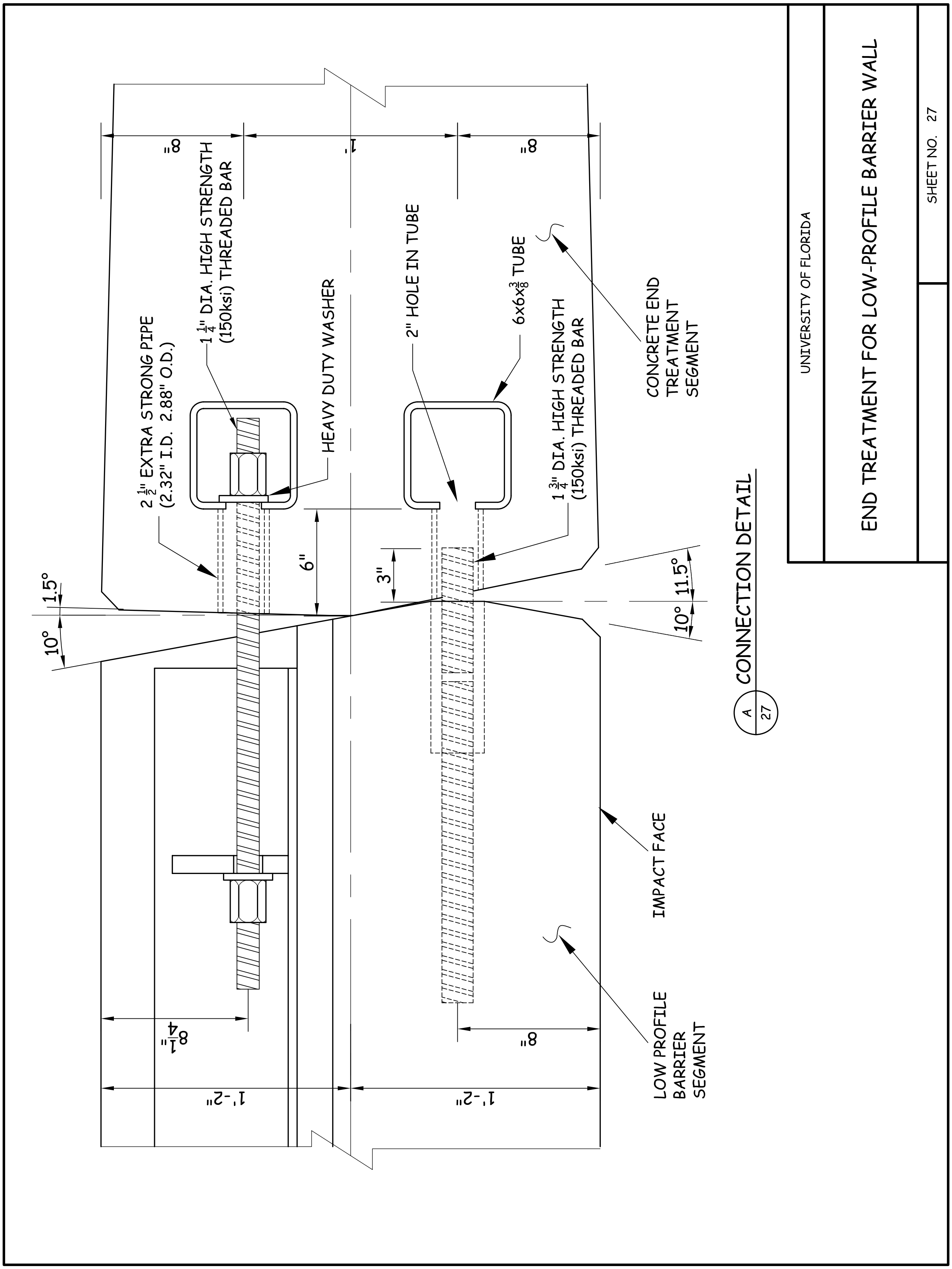

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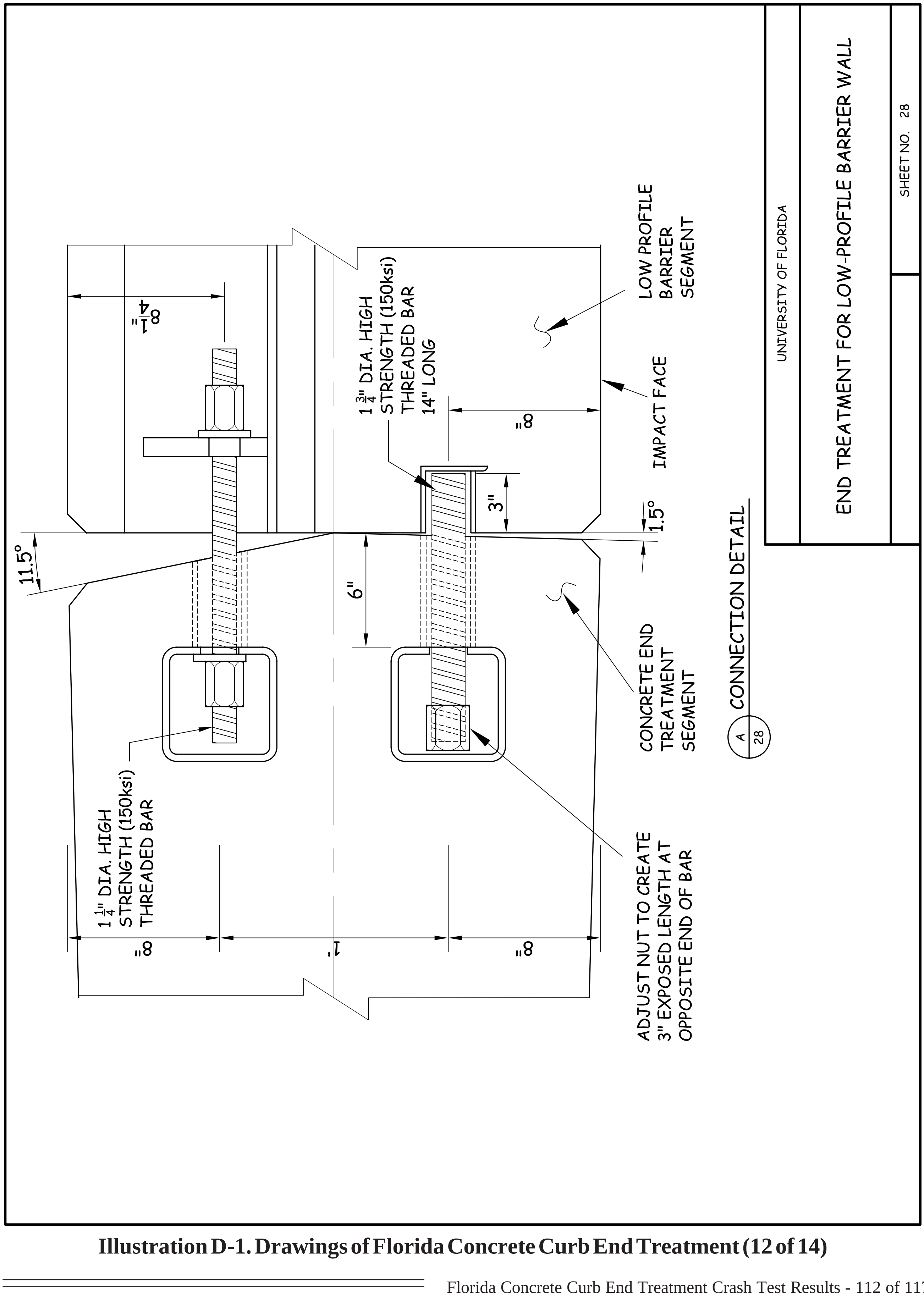

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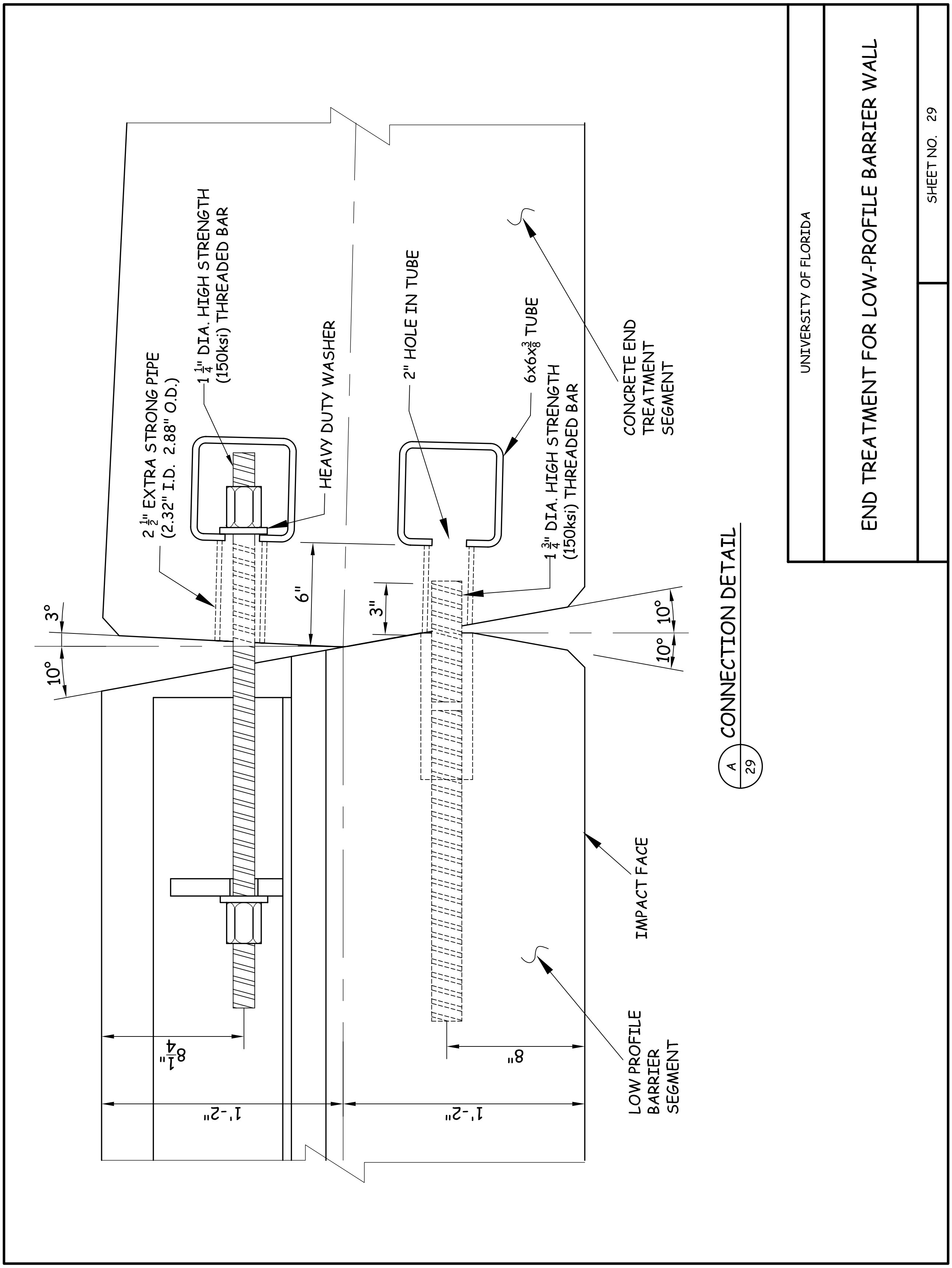

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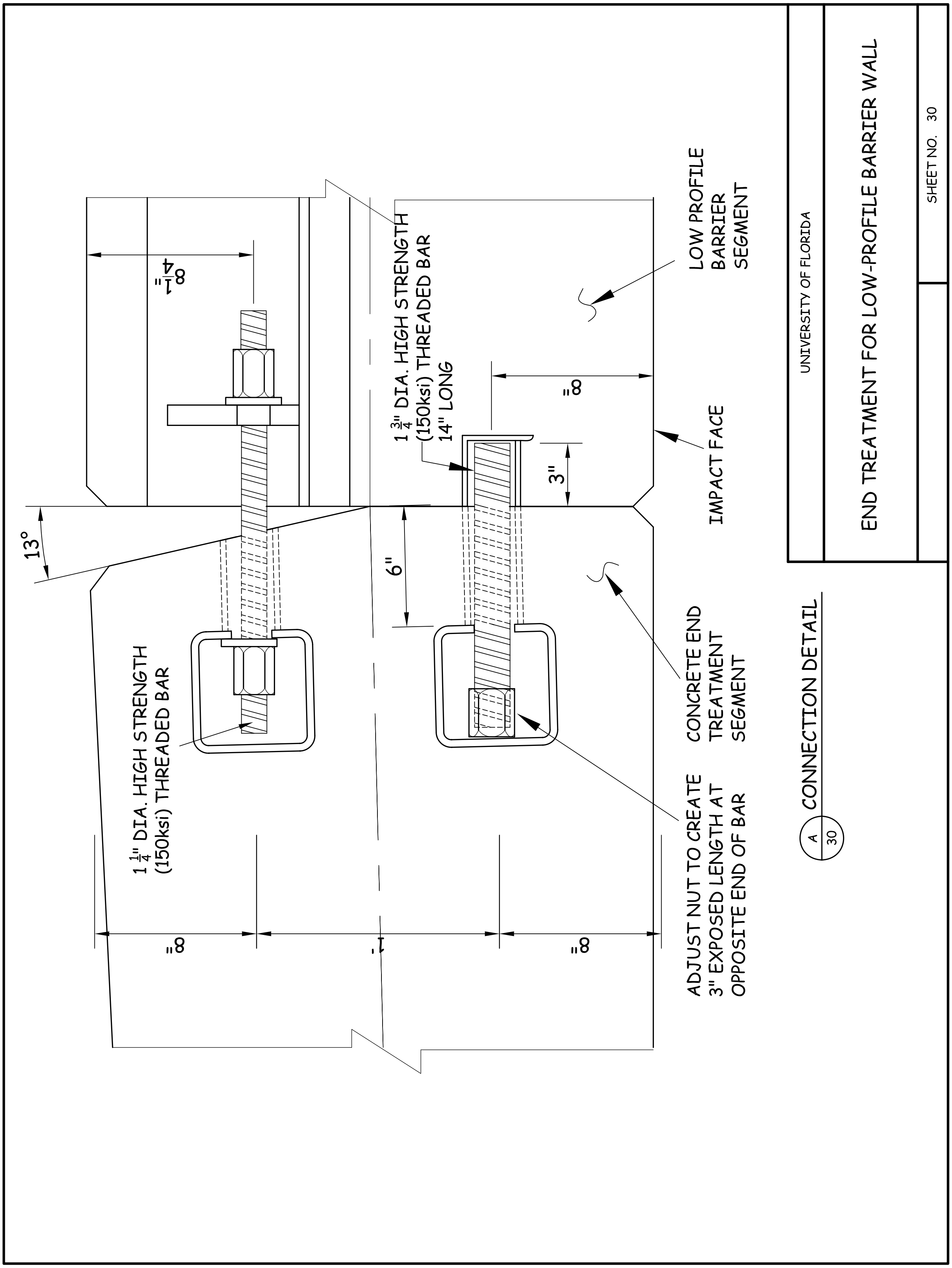

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WILLIAMS FORM ENGINEERING CORP.

Ground Anchor Systems
Concrete Anchor Systems
Post Tensioning Systems
Threaded Bars with Fasteners
Tie Rods Tie Backs
Micro Piles
Concrete Forming Hardware Systems
WILLIAMS CONCRETE ACCESSORIES DIVISION

150 KSI All-Thread-Bar

Threaded Bar Types | 150 KSI Information | 150 KSI Accessories | Case Histories | Corrosion Protection

Structural Properties	
Yield Stress	**Ultimate Stress**
127.7 KSI (880.5 Mpa)	150 KSI (1034.3 Mpa)
Elongation in 20 bar diameters	**Reduction of Area**
4%	20%

Unique Thread Form

R71 150 KSI All-Thread-Bar - ASTM A722

Nominal Bar Diameter	Minimum Net Area Thru Threads	Minimum Ultimate Strength	Minimum Yield Strength	Nominal Weight	Approx. Thread Major Dia.	Part Number
1" (25 mm)	0.85 in^2 (549 mm^2)	128 kips (567 kN)	102 kips (454 kN)	3.09 lbs./ft. (4.6 Kg/M)	1-1/8" (28.6 mm)	R71-08
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1-3/8" (36 mm)	1.58 in^2 (1019 mm^2)	237 kips (1054 kN)	190 kips (843 kN)	5.71 lbs./ft. (8.50 Kg/M)	1-9/16" (39.7 mm)	R71-11
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2-1/2" (65 mm)	5.19 in^2 (3350 mm^2)	778 kips (3457 kN)	622 kips (2766 kN)	18.2 lbs./ft. (27.1 Kg/M)	2-3/4" (69.9 mm)	R71-20
** 3" (75 mm)	6.46 in^2 (4169 mm^2)	969 kips (4311 kN)	775 kips (3448 kN)	22.3 lbs./ft. (32.7 Kg/M)	3-3/64" (78.2 mm)	R71-24

Effective cross sectional areas shown are as required by ASTM A 722-98. Actual areas may exceed these values.
ACI 355.1R section 3.2.5.1 indicates an ultimate strength in shear has a range of .6 to .7 of the ultimate tensile strength. Designers should provide adequate safety factors for safe shear strengths based on the condition of use.
Per PTI Recommendations for Prestressed Rock and Soil Anchors section 6.6, anchors should be designed so that:
- The design load is not more than 60% of the specified minimum tensile strength of the prestressing steel.
- The lock-off load should not exceed 70% of the specified minimum tensile strength of the prestressing steel.
- The maximum test load should not exceed 80% of the specified minimum tensile strength of the prestressing steel.
** The 3" diameter bar is not covered under ASTM A722.

Properties

Williams 150 KSI All-Thread-Bars are manufactured in strict compliance with ASTM A-722-98 and AASHTO M275 Highway Specifications. The prestressing steel is high in strength yet ductile enough to exceed the specified elongation and reduction of area requirement. Selected heats can also pass the 135° supplemental bend test when required. Testing has shown Williams 150 KSI All-Thread-Bars to meet or exceed post tensioning bar and rock anchoring criteria as set by the Post Tensioning Institute including dynamic test requirements beyond 500,000 cycles of loading.

Williams 360° continuous thread deformation pattern has the ideal relative rib area configuration to provide excellent bond strength capability to grout or concrete, far better than traditional reinforcing deformation patterns.

Illustration D-2. Material Specifications (1 of 2)

Seminole Precast Manufacturing, Inc.
Debary, Florida 32713

COMPRESSIVE STRENGTH OF CONCRETE TEST SPECIMENS

Client:	TRANSITION FORM FOR LOW PROFILE	Proj. No:	7504028	Lab I.D. No.	01
Project Name:					
Location:				Cyl:	LP ET
Contractor:				Job Set No.	7850

Mix Type:	CLASS IV	Design Strength:	5500	psi @ 28 days
Admixture:	BORAL LR / BORAL AIR 30	Design Slump :	1.5 to 4.5	inches
Mix Design:	05-0989	Design Air Content:	1.0 to 6.0	%

Date Sampled: 12/13/2007 | Time Batched: | Time Sampled:

Concrete Supplier: Seminole Precast Manufacturing, Inc. | Weather Conditions: Sunny

Ticket Number: 9819

Concrete Truck No.: BP1 | Air Temperature: 80.1 degrees (F)

Size of Load:(yds^3) 01 Yards | Conc. Temp.: 81 degrees (F)

Extra Water Added at the Job Site: ______ gallons to ______ cubic yards

Extra Water Added: ☐ Before and/or ☐ After Slump Test

Extra Water Authorized by: ______ | Sampled by: ALEX

Slump (inches): 5.50 (Truck end of hose) | Air Content (% by vol.) 2.2 | Wet Weight (PCF): ______

DESCRIPTION AND LOCATION OF PLACEMENT:

◉ POURED ○ PUMPED

○ BARRIER WALL ○ COPING ○ FOOTING ○ PANELS ○ PED. BARRIER ○ SOUNDWALL ○ TRAFFIC BARRIER ○ TRAFFIC CURB ◉ OTHER ______ LOW PRO END TR

LOCATION (Column No.'s, Line @ Row. Pad No., etc.)

CYL I.D.	DATE RECEIVED IN LAB	DATE TESTED	AGE (DAYS)	TEST SPECIMEN SIZE DIAMETER (INCHES)	AREA (SQ. IN.)	MAXIMUM LOAD (LBS)	TEST STRENGTH (PSI)	TYPE OF FRACTURE	DEFECTS IN SPECIMEN OR CAP
LP ET	12/13/2007	12/20/2007	7	4.06	12.93	63,647	4922	5	
LP ET	12/13/2007	12/20/2007	7		#N/A		#N/A		
LP ET	12/13/2007	12/20/2007	7		#N/A		#N/A		
LP ET	12/13/2007	12/27/2007	14		#N/A		#N/A		
LP ET	12/13/2007	12/27/2007	14		#N/A		#N/A		
LP ET	12/13/2007	12/27/2007	14		#N/A		#N/A		
LP ET	12/13/2007	1/10/2008	28	4.07	13.00	77,729	5979	5	
LP ET	12/13/2007	1/10/2008	28	4.06	12.93	83,788	6480	2	
LP ET	12/13/2007	1/10/2008	28	4.06	12.87	79,056	6143	5	

ASTM DATA	Y	N	U/K
SAMPLED TO ASTM C-172	X		
MOLDED TO ASTM C-31	X		
INITIALLY CURED TO ASTM C-31	X		
LAB CURED AND TESTED TO ASTM C-31 AND C-39	X		

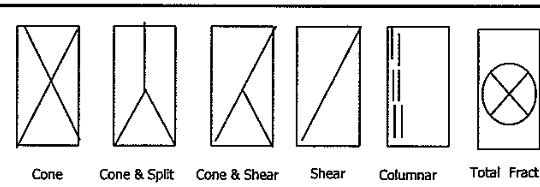

Illustration D-2. Material Specifications (2 of 2)

E. References

1. Transportation Research Board. "Report 350 Recommended Procedures for the Safety Performance Evaluation of Highway Features" Washington, D.C.: National Academy of Sciences, 1993

2. LaTurner, John F. “NCHRP 350 Crash Test Results for the University of Florida Improved Portable Concrete Curb” E-TECH Testing Services, Inc. Report #185, Rocklin, California. November 2002

3. Steinke, Donald P. “Background and Guidance on Requesting Federal Highway Administration Acceptance of Highway Safety Features” FHWA Memorandum HNG-14, U.S. Department of Transportation. 1997.

4. National Safety Council. "Vehicle Damage Scale for Traffic Accident Investigators" Chicago, Illinois, 1984

5. Society of Automotive Engineers. "Collision Damage Classification, Recommended Practice J244a" : SAE, New York, 1972